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SOLID PROPELLANT
STRUCTURAL TEST VEHICLE

SPECIAL REPORT

TECHNIQUES FOR MEASURING STRESS, STRAIN AND TEMPERATURE IN SOLID PROPELLANT MOTORS

NOVEMBER 1971

CONTRACT F04611-70-C-0061

AFRPL

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13. ABSTRACT

This Special Report summarizes experience gained on propellant grain instrumentation during 3 years of effort on the AFRPL-sponsored Structural Test Vehicle (STV) Program. The report discusses the types of stress-, strain-, and temperature-measuring transducers available for use in solid propellant grains, methods of calibrating the transducers, installation techniques, and special handling problems. The report is designed for use as a practical "how to do" guide in the study of propellant grain structural integrity.

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Thermistors						

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BY

H. LEEMING

PRINCIPAL INVESTIGATOR

LOCKHEED PROPULSION COMPANY
P.O. BOX 111 REDLANDS, CALIFORNIA 92373

FOREWORD

This Special Report was prepared under Contract F04611-70-C-0061 for the Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California. The report summarizes the practical experience gained on propellant grain instrumentation during the 3 years of the AFRPL-sponsored Structural Test Vehicle Program.

This Special Report has been reviewed and is approved.

Raymond T Schuder

R. T. Schuder, Capt., USAF
AFRPL Project Engineer

ABSTRACT

This Special Report summarizes experience gained on propellant grain instrumentation during 3 years of effort on the AFRPL-sponsored Structural Test Vehicle (STV) Program. The report discusses the types of stress-, strain-, and temperature-measuring transducers available for use in solid propellant grains, methods of calibrating the transducers, installation techniques, and special handling problems. The report is designed for use as a practical "how to do" guide in the study of propellant grain structural integrity.

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ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

Section 1
INTRODUCTION

The purpose of this Special Report is to assemble in one place the practical experience gained on propellant grain instrumentation during the 3 years of the AFRPL-sponsored Structural Test Vehicle (STV) Program.

Some of the information contained in this report will be found in the earlier STV Final Reports (References 1 and 2). Much of the information has not been published before and is presented here at the request of Capt. Ray Schuder, the AFRPL Project Engineer. He requested a "How To Do" type of report that could be used by those interested in making practical use of the instruments and techniques developed during the STV program. To this end, the body of the report consists of three sections:

Section 2, concerned with strain measuring transducers,
Section 3, which considers stress transducers, and
Section 4, dealing with the measurement of temperature in a solid propellant motor.

The three sections consider, in turn, the types of transducer available, their applications, methods of calibrating the devices, and finally, installation techniques and special handling problems. The report is intended to be practical rather than theoretical.

Because much of the technique for using the various transducers is based on overcoming the gage-propellant interaction problem, two appendixes are included with the report. The first gives a fairly detailed account of the problem of gage-grain interaction so that the reasons for many of the operations will be clear to those who wish to know. The second appendix reviews the theoretical consideration behind the transducer calibration procedures.

It is hoped that this Special Report will prove useful to many people interested in the use of propellant stress-, strain-, and temperature-measuring transducers.

Section 2
STRAIN MEASUREMENT

2.1 TYPES OF TRANSDUCER

Transducers for the measurement of strain are commonly referred to as "Strain Gages". Of the many techniques available for the measurement of strains, the transducer is one of the more fundamental types of measurement. Historically, the majority of the strain measuring techniques was developed for the measurement of extension or deformation of a metallic rod or sheet.

The several types of strain measuring transducer may be broadly categorized as follows:

(1) Surface strain gages
(2) Embedded strain gages
(3) Optical deformation sensors
(4) Optical fringe techniques, e.g., Moiré grid

Other devices may have been used from time to time, but the above comprise the most useful for strain measurement. Following are brief descriptions of these various types of strain transducer.

2.1.1 Surface Strain Gages

These devices, typified by the Baldwin SR-4 electrical resistance strain gages, were designed and made primarily for the measurement of surface strains in metallic components. They consist of either a grid of fine-gage resistance wire attached to a paper or plastic film backing (Figure 2-1),or alternatively, of a grid made of etched metallic foil. Another type of resistance strain gage also is shown in Figure 2-1. This is the "unbonded" strain gage, and in this instance the gage wire is not bonded to the free surface but is wound around pins that are attached to the surface as shown.

More recently, a miniature "solid-state" surface strain gage has been developed, consisting of a small chip or splinter of doped silicon semiconductor material. These gages can be very small, less than 0.05 inch long, and they are very sensitive to the applied strain.

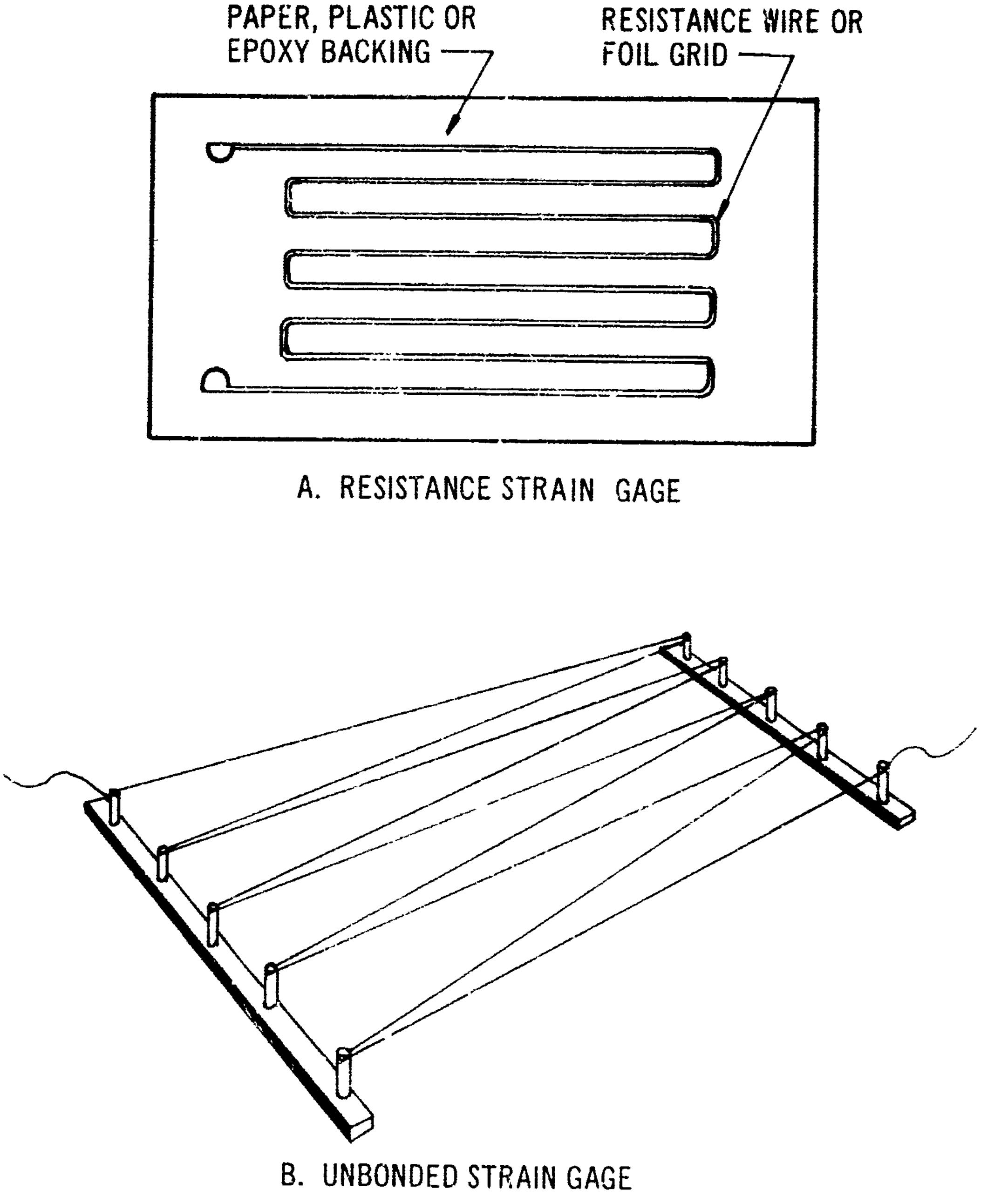


Figure 2-1 Resistance Strain Gages

Despite the physical differences between the different types of strain gage, they all operate on the same principle, as follows:

The gage is firmly attached to the surface under strain with a strong adhesive, typically an epoxy resin. Another, similar gage is attached either at right angles to the first gage, or to another, unstrained piece of metal that is subjected to the same temperature as the strained gage. (The purpose of the second gage is to balance out changes in gage resistance due to changes in temperature. Thus, the gage may be either unstrained, or installed perpendicular to the direction of strain, thereby taking advantage of the Poisson effect and giving an enhanced output signal.)

The two gages are then connected to a bridge circuit, as shown in Figure 2-2, with two fixed resistances used as the other two arms. A supply voltage is connected to the bridge and when the gages are strained, an output signal is produced across the bridge.

The magnitude of this signal is determined from the equation

$$E_o = \frac{E_s}{2} \left\{ (1 + \nu)\, GF\, (\epsilon) \right\}$$

where

E_o = output signal (usually 5 to 10 mv with 110Ω gages)
E_s = supply voltage (commonly 5-volt maximum with 110Ω gages)
GF = "Gage Factor" of strain gages; i.e., change in unit gage resistance for unit applied strain
ϵ = applied strain

The $(1 + \nu)$ factor is only applicable if the second gage is subject to the Poisson strain; otherwise the ν term must be deleted.

It will be noted that the gage sensitivity is determined principally by the "gage factor" of the strain gages. Most normal resistance wire gages have a gage factor of approximately 2.0, but the semiconductor strain gages have gage factors as high as 150.0, which makes them considerably more sensitive.

Semiconductor gages have found considerable use, therefore, where high sensitivity is required, and they operate at much lower current levels than the wire or foil gages. A major problem with semiconductor strain gages is their marked change in resistance with temperature, which results in large output signals under transient thermal conditions unless precautions

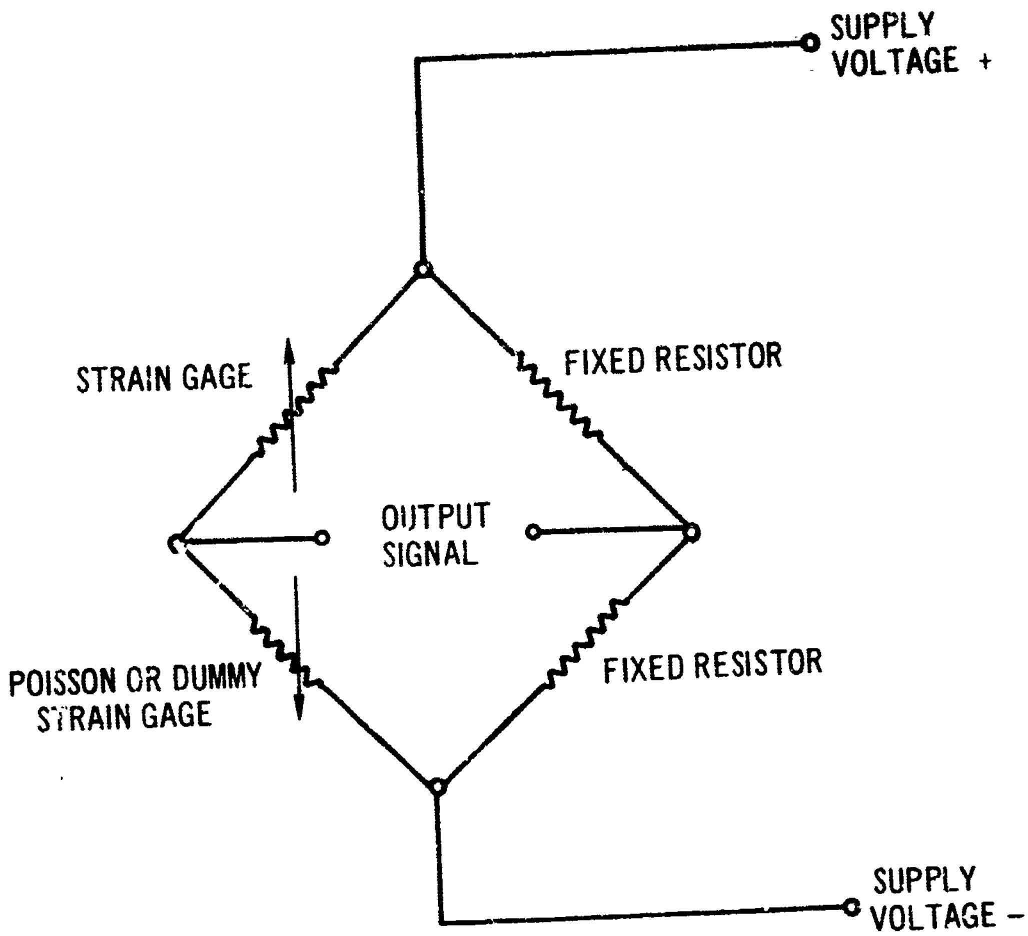


Figure 2-2 Resistance Strain Gage Bridge Circuit

are taken to eliminate the effect. The use of Wheatstone bridge circuits and the addition of series and parallel passive resistors across the gage elements have enabled these devices to be used across a wide range of temperatures with virtually no change in thermal zero signal and almost no change in gage sensitivity (Ref 2).

2.1.2 Clip-Type Surface Strain Gages

The problem with the conventional surface strain gages is the fact that they can be used only on a rigid surface, such as a metal motor case, if precise strain values are required. They cannot be used as strain gages in conjunction with soft elastomeric materials such as propellant. The gage element is much stiffer than the propellant surface so that the gage cannot deform with the propellant. Consequently, erroneous strain measurements would result.

Thus, for the measurement of surface strains at the bore of a propellant grain, the clip gage illustrated in Figure 2-3 has been developed.

The gage consists of a small clip made from thin metallic foil to which are attached two resistance strain gages, as shown. When the two feet of the clip gage are displaced relative to each other, the central beam of the clip is subjected to bending, which produces a tensile strain in one of the strain gages and a corresponding compressive strain in the other gage.

Both foil strain gage elements and semiconductor strain gages can be used with the clip gage. The semiconductor gages produce a more sensitive surface strain measuring device, but with a more restricted range of strain. A detailed description and evaluation of the clip gages will be found in Rocketdyne's Transducer Development Program Final Report (Ref 3). This type of gage has proved extremely accurate in the laboratory for small displacement measurement, and it has also given good results in motor tests, such as those of the STV program at LPC and the Minuteman program (Rocketdyne, Ref 4).

The major problem with the clip gage is the method of attaching the gage to the surface of the propellant grain. Apart from the obvious difficulty of being able to reach far enough inside the grain to place the gage in the desired location, it was found that simply bonding the tabs to the grain surface, as shown in Figure 2-4(a), was unreliable. In fact, the gages

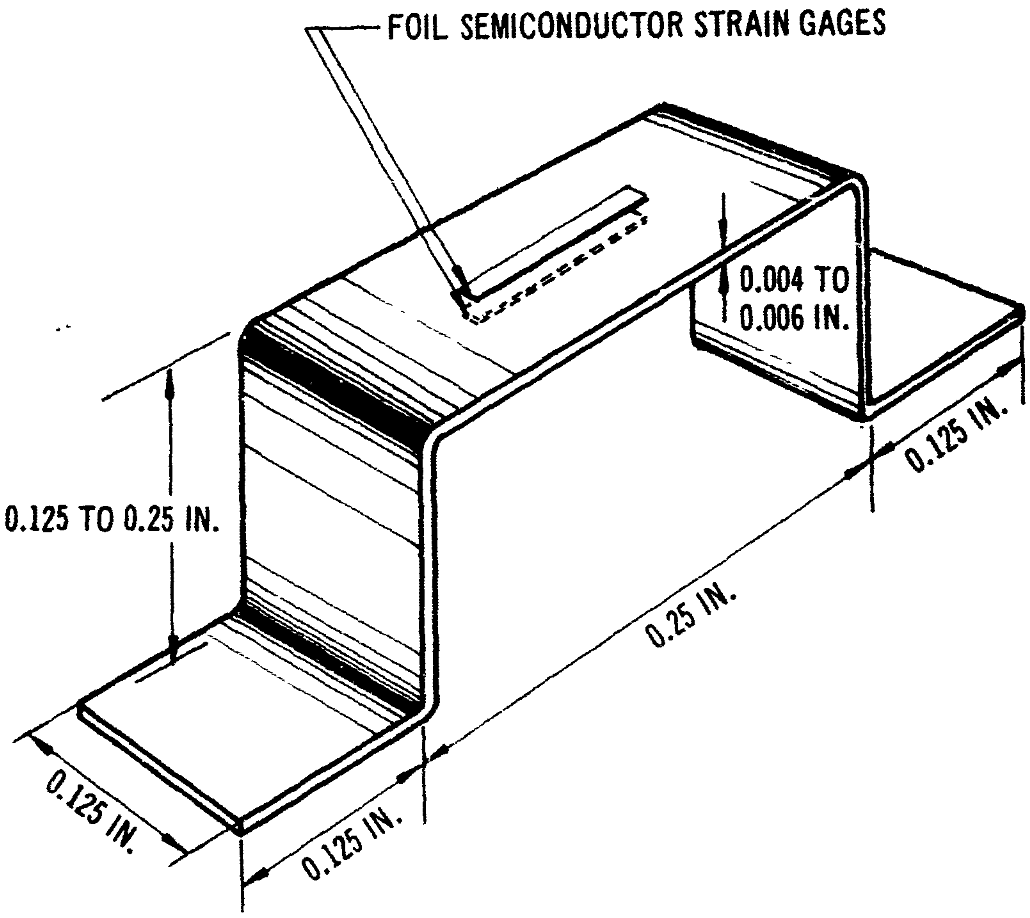
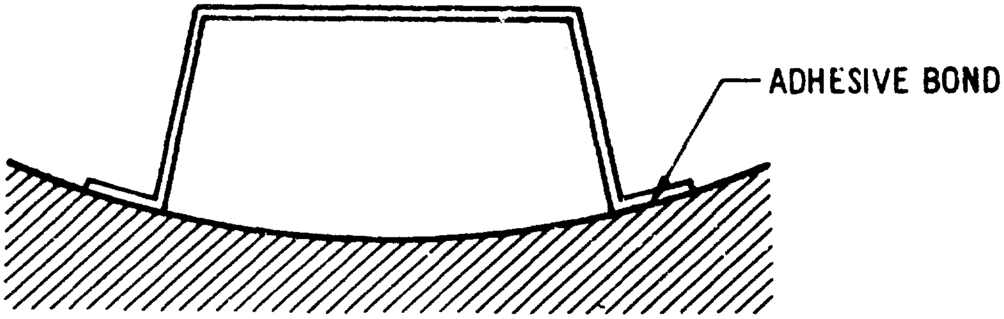
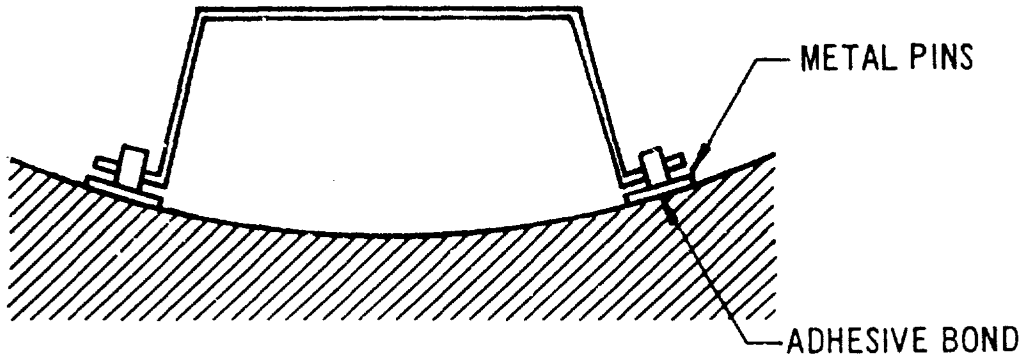


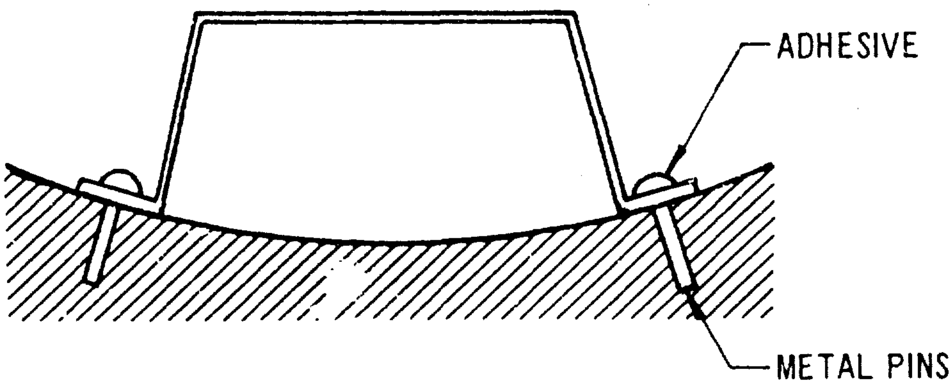
Figure 2-3 Free Surface Clip Type Strain Transducer



(A) ADHESIVE BONDING OF TABS TO PROPELLANT SURFACE



(B) ADHESIVE BONDING OF SEPARATE PINS TO PROPELLANT SURFACE



(C) USING PINS EMBEDDED IN THE PROPELLANT GRAIN

Figure 2-4 Techniques for Attaching Surface Clip Gage to Propellant Grain became unbonded during thermal cycling tests of the STVs. Alternate methods devised to solve this problem are illustrated in Figure 2-4(b) and (c).

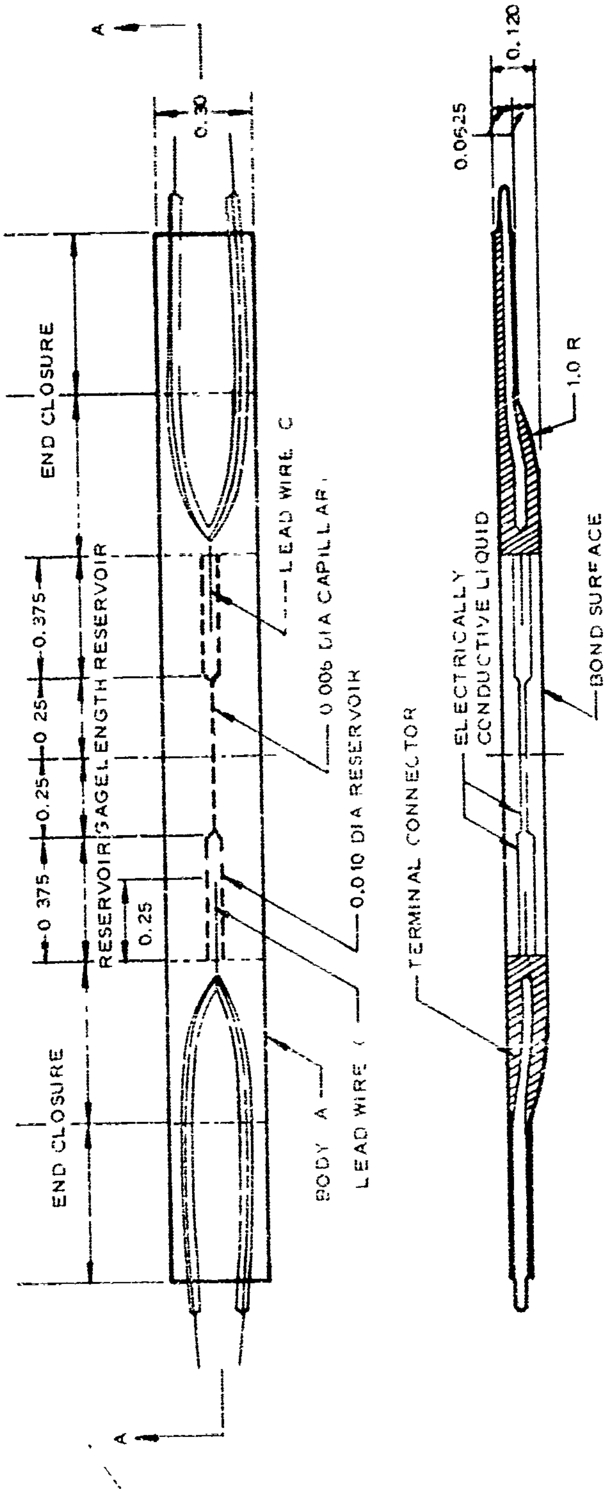
Rocketdyne's solution to the problem was to bond small feet to the surface of the propellant, as shown in Figure 2-4(b). The clip gage has holes drilled in the tabs, which locate on the turned-down section of the pins. In this manner the precise gage length is predetermined and the bench calibrations may be used with confidence.

Because of the possibility of failure of the adhesive bond between the feet and the propellant surface under repeated thermal cycles, the technique shown in Figure 2-4(c) was adopted at LPC to install surface measuring strain gages in the Bomb Dummy Unit Flight Test Vehicle. Metal pins are smeared with adhesive, pushed into the propellant surface, and bonded in place. The clip gage with holes drilled in the tabs is then fitted in place onto the pins and small amounts of epoxy adhesive are placed on the top surface of the tabs to prevent the clip gage from falling off. While this is the most positive technique available for attaching the surface clip gages, it cannot be used in a situation of very high strain because insertion of the pins could cause cracking of the propellant grain. This approach is therefore not suitable for the measurement of surface strains up to failure conditions.

Another type of problem that may be encountered with the clip gage is resonance of a part of the gage during vibration testing. This has not been observed during operational use of the clip gages but it is clear that some resonance effects must be anticipated if the excitation frequency becomes high enough. A possible method of eliminating or minimizing this problem would be to affix a small piece of foam rubber to the inner surfaces of the clip gage. The foam would not apply a significant force to prevent slow frequency displacement but should supply damping at high frequencies and thereby prevent or at least reduce any resonant displacement.

2.1.3 Elastomeric Surface Strain Gages

A surface strain measuring device developed especially for use with soft materials such as propellant is the mercury-filled elastomeric gage of the South West Research Institute (SWRI), as shown in Figure 2-5. This



GAGE RESISTANCE 0.30-0.60 OHMS
MATERIALS
A GAGE BODY - POLYURETHANE, TOLYLENE DI-ISOCYANATE
B ELECTRICALLY CONDUCTIVE LIQUID MERCURY BASE ALLOY
C TERMINAL CONNECTING - COPPER WIRE

Figure 2-5 Southwest Research Institute (SWRI) Elastomeric Surface Strain Gage device approaches the ideal of a zero-stiffness and hence a zero-force strain sensor because the measuring element is an elastomeric tube filled with an electrically conductive liquid (mercury alloy).

Unfortunately, the chief virtue of this device is also its major drawback. Because the sensor is a liquid contained within an elastomer, it deforms readily with the surface to which it is attached and applies negligible restraint to that deformation. By the same token, the device does not have a well-defined zero strain configuration and consequently the data from the gage are somewhat unreliable and unrepeatable. This type of gage is more suited to qualitative rather than precise quantitative measurements of surface strain.

The development of this type of surface strain gage is described in Reference 5, and an evaluation of the gage may be found in Rocketdyne's final report, Reference 3.

Another type of surface strain measuring sensor can be made from conducting polymers, such as Union Carbide's material DQDA. Under mechanical deformation this material changes its resistance so that it may be used as a strain sensing element. Again, this type of material has suitable physical properties in that it has a low modulus similar to that of propellant.

Apart from the dimensional stability problem, which affects this type of elastomer in the same manner as it does the SWRI strain gage, the conducting polymer type of material also was found to have another drawback. This is the extreme sensitivity of gage resistance to changes in temperature. Typically, resistance may change from 200,000 ohms at 0^{0}F to 200 megohms at 200^{0}F; i.e., a change of three orders of magnitude.

Although the majority of this resistance change may be eliminated by using pairs of sensors in a bridge circuit, it is doubtful if the strain sensitivity would stand out amongst the thermal error signals.

2.1.4 Embedded Strain Gages (Shear Gages)

In this discussion the problems associated with the use of embedded transducers will be ignored and comments will be confined to the devices themselves. A later section will cover the gage-grain interaction problem and the interference problem associated with embedded gages.

Although it is possible to consider any of the various types of surface strain measuring gages as embeddable gages, in practice the only type of embedded device that has been used to any extent is the embedded shear strain gage. Several types of shear gage have been developed over the past decade for the measurement of shear strain at the propellant-case interface of a solid propellant rocket motor. Several of these devices are sketched in Figure 2-6.

The first embedded shear gage is the shear cube developed at LPC from the shear transducer manufactured by Gulton Industries for the Hercules Powder Company (Ref 6). The transducer is simple, containing a pair of semiconductor strain gages mounted perpendicularly to each other and at a 45-degree angle to the mounting surface of the cube. In operation, the two gages are connected in a Wheatstone bridge circuit, as shown in Figure 2-7, to measure either the shear strain in the shear mode of connection, or the normal strain in the normal mode of connection.

When the gages are connected in the shear mode, changes in gage resistance caused by temperature effects are largely self-compensating, providing that the two gage elements are well matched. In the normal mode of connection, however, the thermal resistance changes in the gage elements do not cancel one another so that there is a large variable output as a function of temperature, and the strain effects must be obtained from this variable baseline. This means that the normal strains cannot be measured as accurately with the shear cube as can the shear strains.

The shear transducer shown in Figure 2-6(b), is the device developed by The Boeing Company for the measurement of interfacial shear deformation at a propellant-case interface (Ref 7). A shear strain applied to the block of low-modulus rubber produces bending in the strain-gaged metal element and provides an electrical signal from the bridge circuit. The four-active-gage configuration provides a very sensitive type of shear gage.

A similar type of shear strain measuring transducer is shown in Figure 2-6(c). In this case, the application of shear strain to the propellant or elastomer causes the beam to bend and produces an electrical output signal from the two strain gages mounted on the deflecting beam. By a suitable choice of metal element thickness, the range of both of these types of transducer can be varied between wide limits.

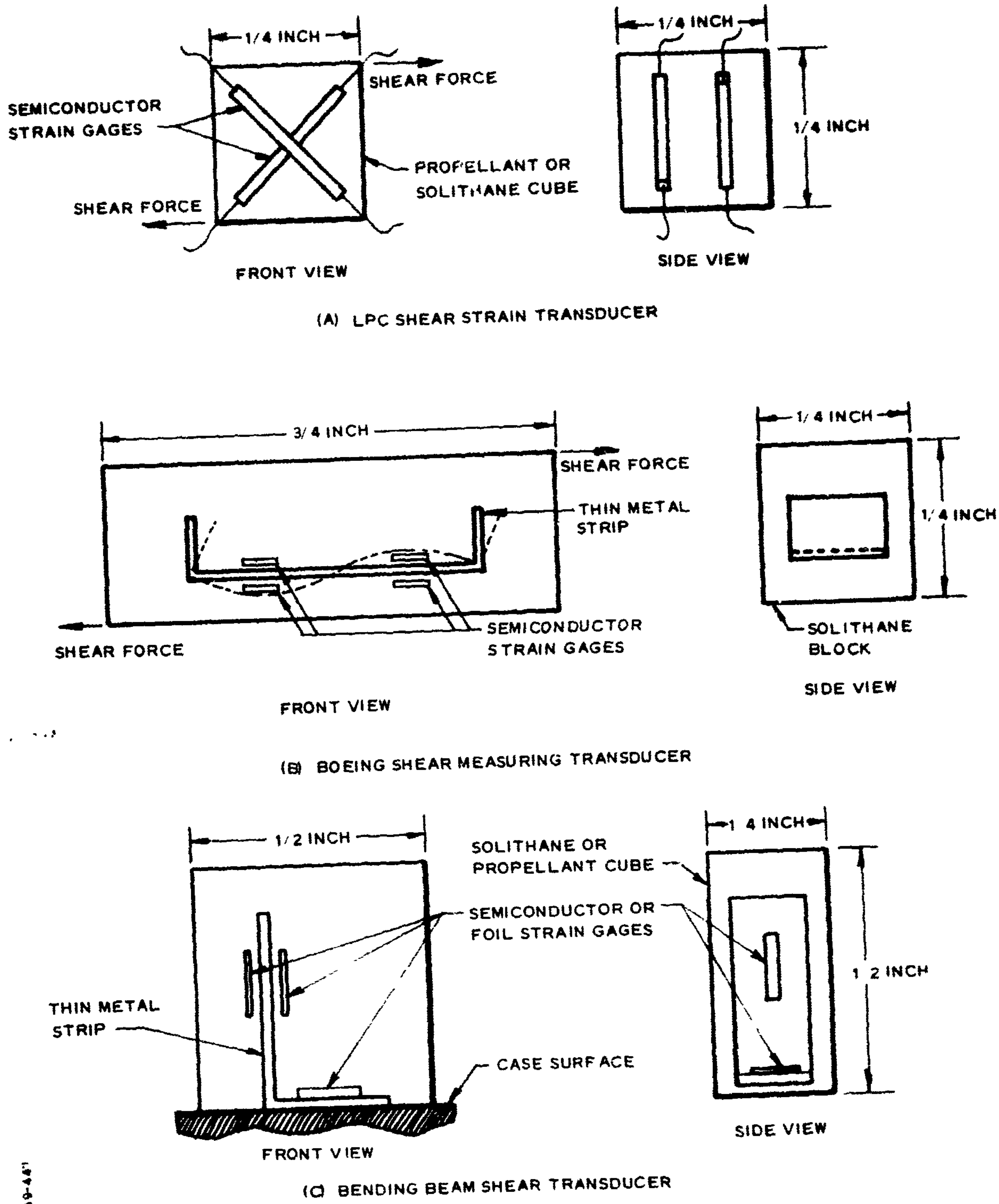
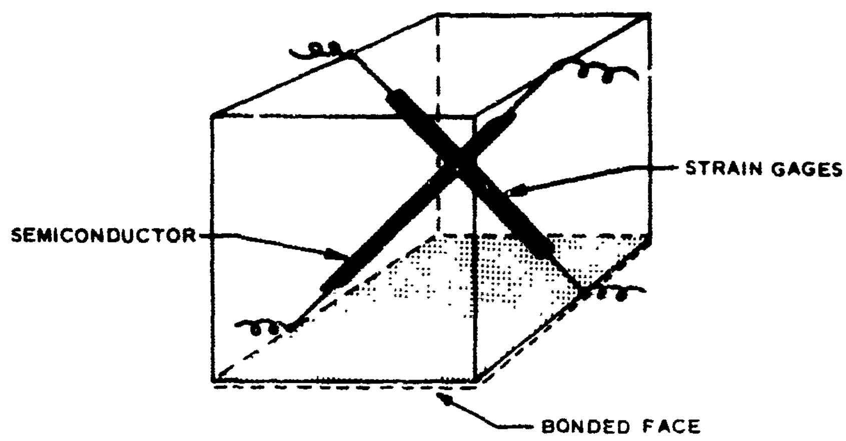


Figure 2-6 Embedded Shear Strain Transducers



SHEAR CUBE CONFIGURATION

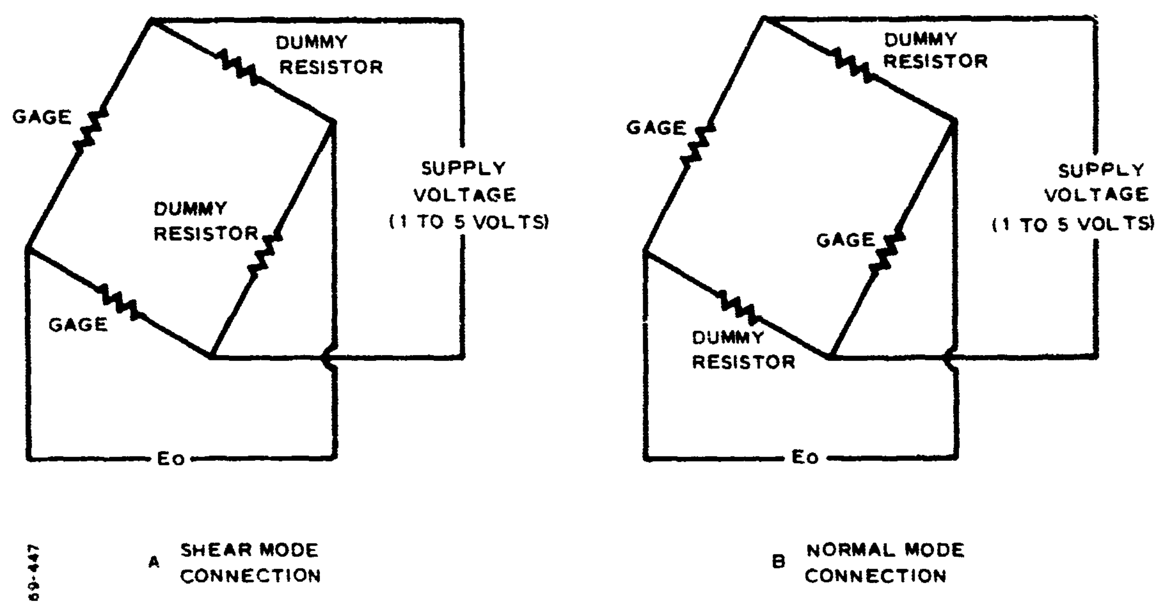


Figure 2-7 Shear Cube Configuration and Modes of Connection

Advantages of the embedded strain measuring devices of the types described above include the following:

(1) They are essentially simple devices and could be relatively inexpensive.

(2) They can be extremely sensitive.

(3) Their range of measurement can be changed within wide limits.

(4) They can be arranged to measure shear or normal deformations.

Disadvantages of this type of deformation transducers include the following:

(1) The inclusion of the strain gages or metallic elements disturbs the stress and strain field locally.

(2) The possibility of slip between the elements and the matrix may lead to lack of repeatability of data, especially under varying temperature conditions.

(3) They are not suitable for measuring high local surface strains that may occur at the bore of a grain.

However, this type of embedded shear strain measuring device has been used with considerable success in the development of motors such as SRAM and in the flight tests of motors for high acceleration conditions, e.g., Hibex and Sprint. Their biggest problem is that they are incapable of resolving a complex strain field into just the shear component. Thus, the output signals from these gages will be influenced by components of the strain field other than the shear component. They should not be used, therefore, under conditions of complex stress/strain environment, such as the termination points of a grain.

2.1.5 Optical Surface Strain Measuring Techniques

Although many devices employing the optical lever principle have been used for the measurement of small displacements, the most common type of optical device used for measuring surface strains is the Moiré grid technique. The Moiré method has been used extensively to determine surface strains in metals, plastics, and propellants (Ref 8 through 12).

The Moiré effect is an optical phenomenon produced when two similar arrays of dots or lines are superimposed, resulting in the formation of alternating light and dark fringes. Since the fringes are the result of relative displacement of the two arrays, they may be used as a tool for making strain measurements. The sensitivity of the system depends on the spacing of the grid lines.

Methods have been developed for measuring local strains on propellant surfaces and on curved surfaces, e.g., the internal bore of a propellant grain. Grid systems with 350 lines per inch have been used routinely in studies on propellant.

The method of using the Moiré grid technique on propellant specimens is illustrated in Figure 2-8. A compatible white latex paint is first sprayed onto the propellant surface and a grid is photographically imprinted onto the paint. An identical "master" grid is printed onto a thin, flexible, transparent sheet, and a thin coat of silicone grease is used to hold the master grid against the propellant surface. When the propellant strains, the grid on its surface distorts and moves relative to the master grid, thereby creating the Moiré fringes.

This technique closely approaches the ideal of a zero resistance surface strain gage, the slight resistance due to the silicone grease being the only restraint on deformation.

2.2 APPLICABILITY OF STRAIN TRANSDUCERS

2.2.1 Resistance Strain Gages

The main application for conventional foil or semiconductor strain gages is for the measurement of the strain induced in inert motor components such as the motor case, the nozzle, and other inert components. Gages of this kind are intended to be used on rigid surfaces and preferably on metallic components. Depending on the precision required of the strain measurement, it is possible to obtain gages made especially for attaching to a given type of metal, and providing a precise match for the thermal coefficient of expansion of that metal.

Motor case strain measurements may be used, for example, to investigate the design of a case under firing conditions, or to determine the bending

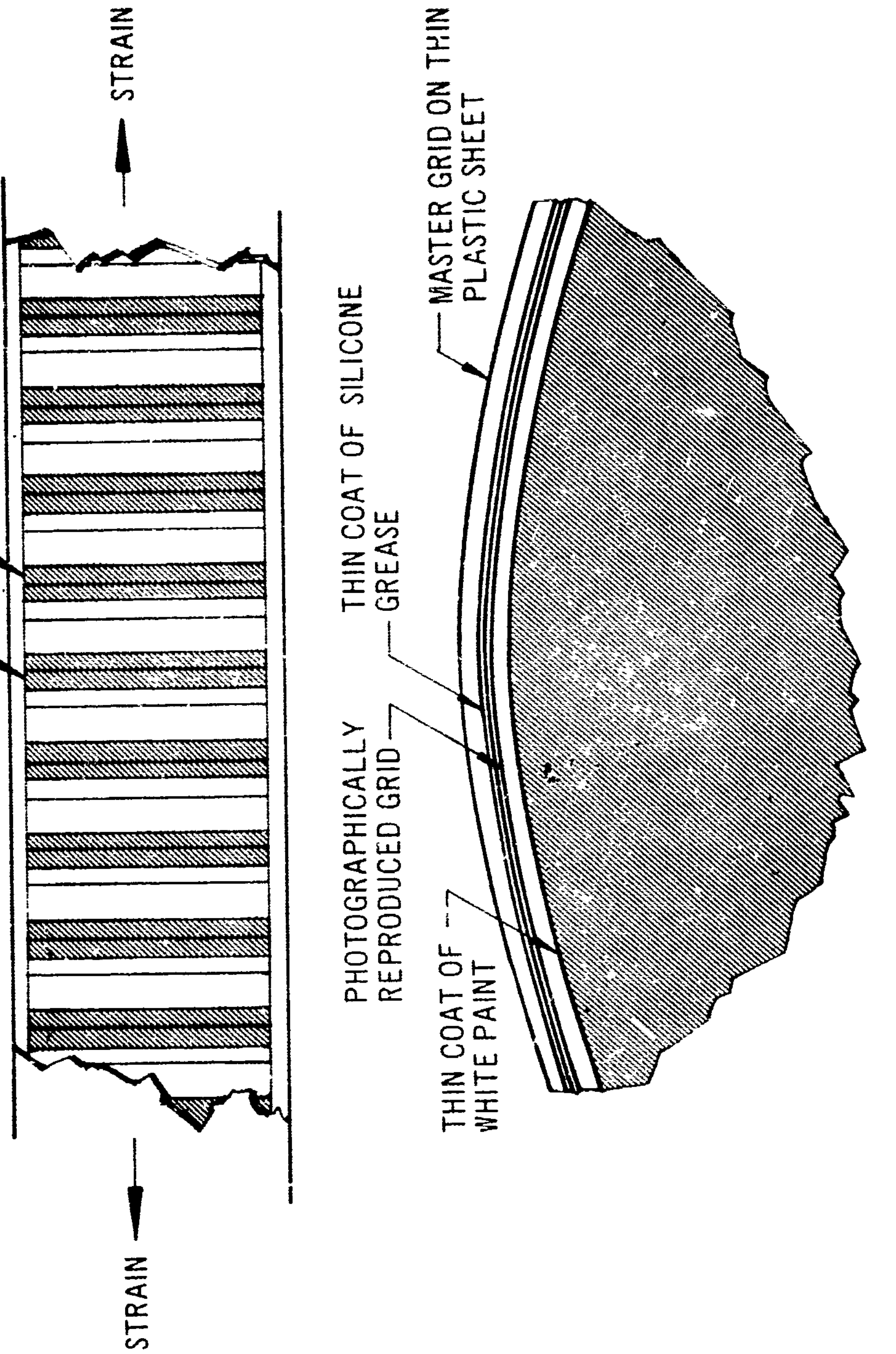


Figure 2-8 Method of Using the Morié Grid Technique on a Propellant Specimen

strains resulting from flight-type loads. They may even be used as an indication of the thermally induced interfacial tensile stresses, providing that the sensitive semiconductor type of gage is employed.

2.2.2 Clip-Type Surface Strain Gages

Clip-type devices are designed to monitor the strains induced in relatively soft materials such as propellant, soft plastics, or rubbers. They may be used to monitor slowly changing or static-type loadings, or they may also be used for the measurement of dynamic (vibration) loads for frequencies up to approximately 1000 Hz. (They will also measure higher-frequency deformations, but may require special damping to eliminate internal resonances within the clip gage.)

2.2.3 Elastomeric Surface Strain Gages

Devices such as the SWRI mercury-filled elastomeric strain gages were developed primarily for the measurement of surface strains on soft materials such as propellant or rubber. They are devices essentially for measuring approximate strain values under conditions when no other gage will perform, e.g., in measuring the failure strain at the bore of propellant grains.

The strain values derived from these gages must be used with caution, and the possibility of a considerable error band must be recognized. It is known that several companies have used the devices for motor failure strain measurement with some degree of success. It is recommended that these devices be used in groups so that several readings of a strain value can be obtained. If the various gages all read approximately the same strain value, then it may be assumed that the datum point is real.

2.2.4 Embedded Strain Gages

The embedded types of strain gages discussed earlier were developed especially for the measurement of strain at the case-propellant interface of a solid propellant motor. Their principal use, therefore, is for the measurement of interfacial shear strains in relatively soft elastomeric materials. The shear cube may also be used to measure normal strains but is not so accurate when connected for such measurements as it is for shear strain measurements.

Generally, the material or matrix surrounding the gage elements or the bending clip will be the same as that of the propellant grain. This method provides the most accurate shear data. If another material is used for the gage, then there will be a slight mismatch between the matrix material and the propellant grain, which can impair the accuracy of the gage data. However, in some instances the slight reduction in accuracy is more than compensated by the reduced safety hazard when the gage element is embedded in an inert material, e.g., a dummy propellant. For example, during the early stages of the STV program an attempt was made to apply excessive current through four gages embedded within a small cube of live STV propellant. All four gages were connected in parallel and increasing voltage was applied to them. Eventually the gages burned out, in this instance before enough local heat was generated to ignite the small propellant cube. Ignition of a more sensitive propellant could result from the application of an excessive voltage to an embedded gage. For this reason, the operating current in the semiconductor strain gages is usually maintained at about 1.0 ma, thereby keeping heat dissipation through the gage to a very low level. To maintain the 1.0-ma current maximum, the bridge voltage should not exceed 2 volts for a shear gage made from live propellant. This will still provide a gage sensitivity of 20 mv/psi shear.

2.2.5 Moiré Grid Technique

The Moiré approach may be used to measure surface strains on any exposed surface that is flat or nearly flat. The surface has to be visible so that the fringes can be observed and counted. Special techniques can be used to measure the strains on curved surfaces by means of Moiré grids, as described in Reference 9.

The Moiré technique can be used to measure the strains of soft materials such as plastics, propellants, or rubbers, and it applies negligible restraint to the deformation of the surface.

2.3 CALIBRATION TECHNIQUES FOR STRAIN GAGES

2.3.1 Resistance Strain Gages

Resistance strain gages are now made so accurately that it is seldom necessary to calibrate the gage itself. In some applications variations in the thickness of the adhesive used to bond the gages in place can produce significant changes in response, necessitating an independent calibration of the system.

A common method of calibrating the specific gage-adhesive-substrate system is to bond two gages to a length of the substrate material and test the system in a bending test. The precise strain applied to the gages can readily be determined and, from the gage output, the effective "gage factor" for the system can be measured. The assumption is then made that this effective 'gage factor' will be repeated on the actual gages in the operational test mode.

In most practical applications, however, the gages are simply mounted on the surface to be strained, e.g., the exterior of a motor case, and the gage factor supplied by the manufacturer is employed to determine the case strain.

For semiconductor strain gages, the gage factor should not be assumed without checking. It is preferable in using these devices to perform a complete calibration of the gage circuit across the whole temperature range under consideration, and with the recommended type of power supply.

In using semiconductor strain gages, it should be realized that circuit changes should not be made without determining the full effects of the changes across the whole temperature range. For instance, the circuit generally employed with semiconductor strain gages is shown in Figure 2-9. Unlike the foil gages, the bridge circuit is usually supplied through a dropping resistor R_D from a relatively high voltage supply, e.g., 20 to 28 volts. This high voltage power supply, in conjunction with the high-value dropping resistor, has the effect of minimizing current changes through the gages as the gages change resistance with temperature. The large series dropping resistor produces a condition of almost constant current supply instead of the constant voltage supply used with foil gages. A manufacturer using semiconductor gages for a high-precision measuring instrument will

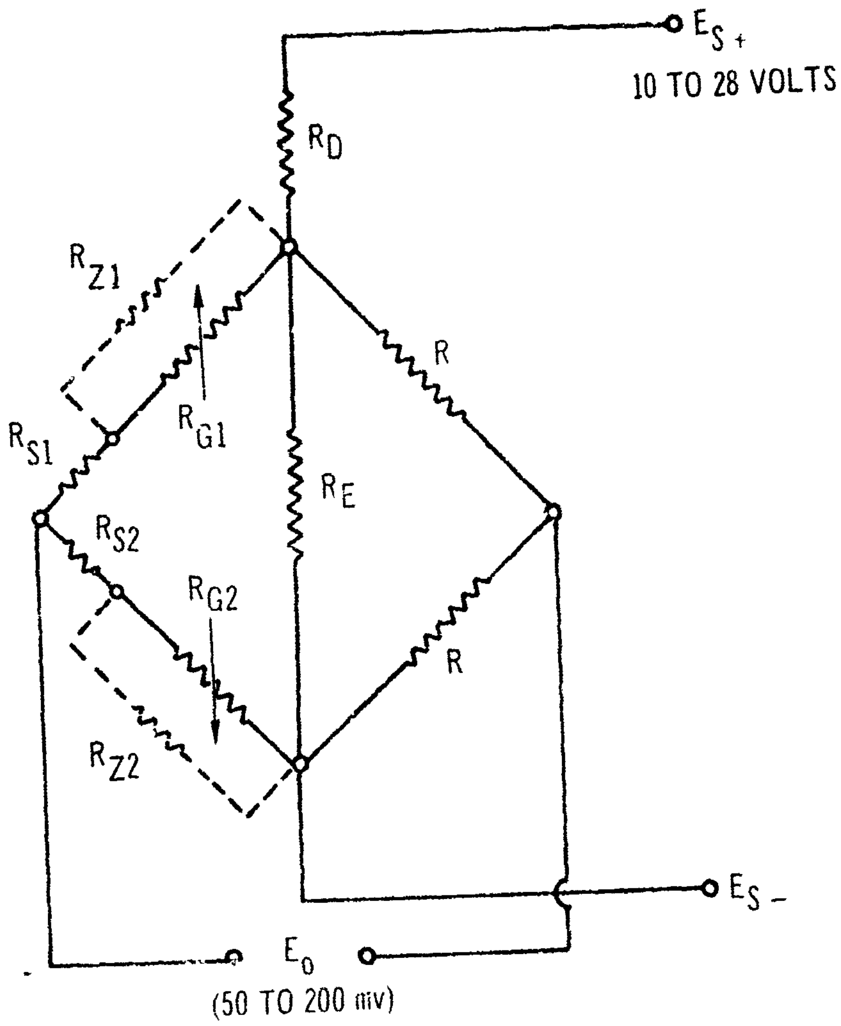


Figure 2-9 Bridge Circuit for Semiconductor Strain Gages

investigate combinations of different power supply voltages in conjunction with different values of series and parallel supply resistors to obtain the best compromise in the sensitivity-versus-temperature curve. A condition somewhere between constant voltage and constant current is usually required to provide the best (most nearly constant) gage sensitivity as a function of temperature.

The additional resistors R_s and R_z found in an operational semiconductor gage circuit are inserted to minimize the change in zero reading as a function of temperature. Thermal output signals result from small differences in the change in gage resistance with temperature for the two gages in the bridge circuit. To minimize this effect, the gage that shows the largest change in gage resistance with temperature is shunted with a large-value resistor R_z, which will reduce the change in resistance with temperature. The shunting resistor will cause an "out-of-balance" in the bridge circuit at ambient temperature, which is eliminated by the addition of the small series resistor R_s.

By investigating several combinations of series and parallel shunt resistors across the required temperature range, the gage manufacturer is able to obtain the minimum change in gage zero load output signal.

In view of the precautions taken to produce very small changes in gage sensitivity and zero drift, it is clear that resistance changes should not be made without a careful review of the consequences. This includes the use of shunt resistors to produce zero gage output under a given load condition. Such resistors may completely change the zero output signal of the gage circuit. Similarly, it is not good practice to operate semiconductor strain gage bridge circuits with low-voltage supplies and simply eliminate the dropping resistor. This can produce a significant change in gage sensitivity with temperature.

It is hoped that the foregoing remarks will not be construed as intending to imply that semiconductor gages are difficult to use. This is not true. However, they cannot be used with the same simple approach as can foil gages. If due precautions are employed in their use, then the very significant advantages afforded by the high gage factor can be exploited to the fullest extent.

2.3.2 Clip-Type Surface Strain Gages

Thermal calibration. If the clip gage is to be used for the measurement of surface strains across a range of temperatures, then the thermal zero strain output signal from the clip gage must be determined as a function of temperature. Probably the best technique is to use a small block of Invar to which are bonded two small pins with enlarged bases. Holes drilled in the tabs of the clip gage locate on the two pins and hold the gage firmly in place. The essentially zero coefficient of linear expansion of the block of Invar maintains the feet of the clip gage at a constant distance apart across the whole range of temperature required. The gage mounted on the block is placed in a temperature-conditioning box and the temperature is set at a desired value. Sufficient time is allowed for the gage and block to attain thermal equilibrium before a reading of the gage output signal is taken. The chamber temperature is then changed to another value and, after thermal equilibrium is attained, another gage reading is taken.

In this manner the gage output readings for a fixed and known displacement between the feet of the clip gage are determined for a wide range of temperatures.

This technique, adopted by the Rocketdyne Instrumentation Laboratory, is probably the most accurate method of thermal calibration available. For many applications it is unnecessary to go to this length. The clip gage may be mounted on a piece of steel instead of Invar, and the thermal zero strain gage readings taken as before. In this case, however, the steel block will be changing dimensions slightly with temperature so that the actual gage readings must be corrected for the thermal expansion or contraction of the steel block in order to determine the precise zero strain readings. Depending on the use to which the gage is to be put, this small correction factor may be ignored, especially if the change in readings is small and the gage sensitivity to strain is very high; a common situation with the clip-type surface strain gages.

Strain calibration. To calibrate the clip gages for strain, a small tool is used, equipped with a pair of jaws that can be moved relative to each other either by a micrometer screw or a vernier slide. The two pins are bonded to the jaws of the device, as shown in Figure 2-10, and the clip gage is fixed in place, using a small amount of adhesive, if necessary.

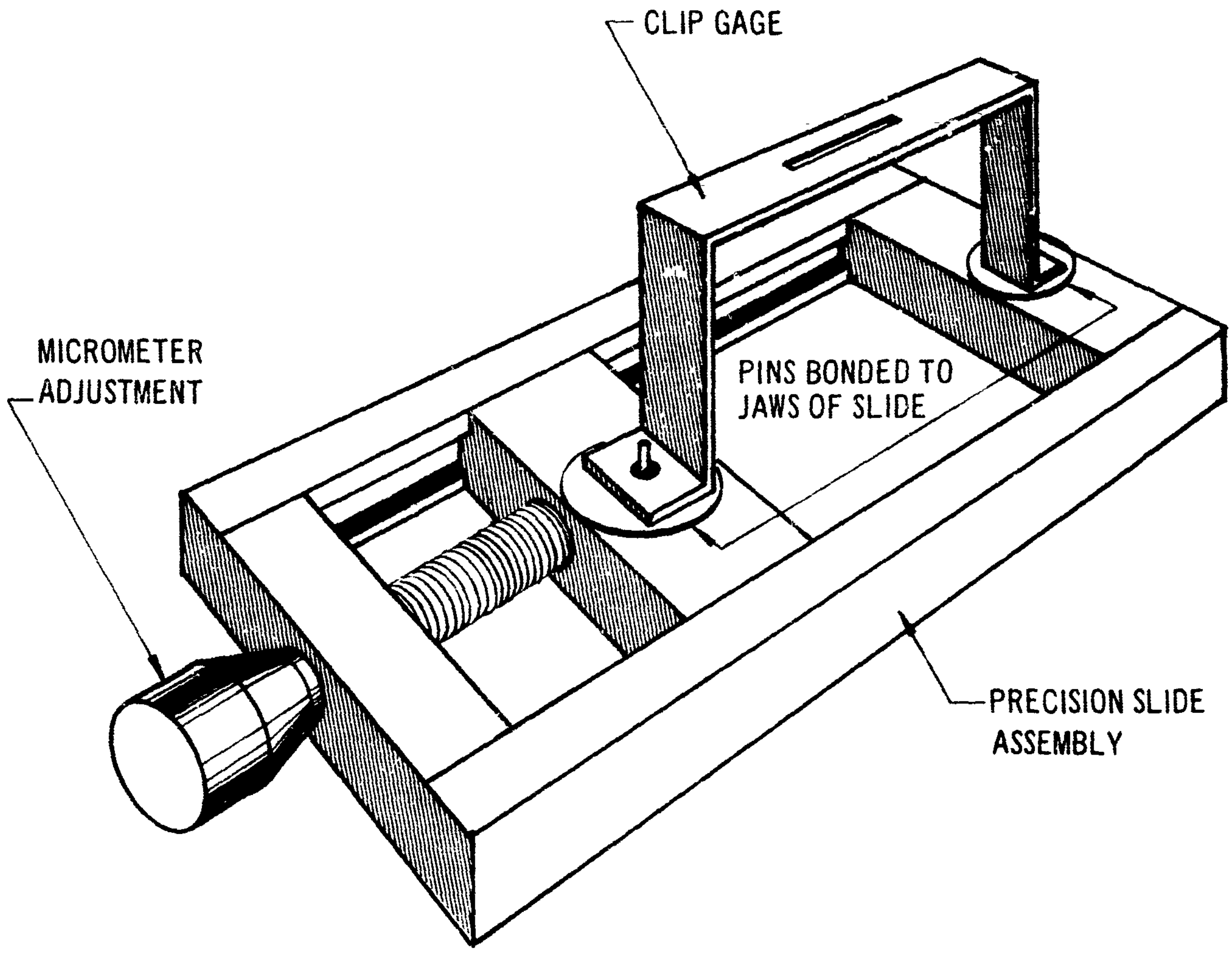


Figure 2-10 Calibration Fixture for Clip Gage Strain Calibration

Readings of the clip gage output signals for various displacements of the jaws of the device can then be made at a series of fixed temperatures. The common practice at LPC has been to use the displacement device for determining the thermal zero readings as well as the strain calibration readings. In this way, the two pins have to be bonded only once to the jaws of the calibration device, and the thermal zero readings are made with the jaws set to a known relative displacement.

Once the thermal and the strain calibration data are obtained, they should be plotted as two separate graphs: (1) gage signal versus strain, or relative displacement of the clip gage feet, for a constant value of temperature, and (2) gage signal versus temperature for a constant separation of the feet of the clip gage (see Figure 2-11). With these sets of data the gage readings can be quickly interpreted as strain whether the problem be isothermal pressurization or slow thermal cooling of a motor.

After calibration is completed, the clip gage can be removed from the calibration fixture and is then ready for installation in the motor.

2.3.3 Elastomeric Surface Strain Gages

Elastomeric strain gages cannot be calibrated in a manner precisely identical to the way they are used in a motor because they must be bonded in place. Once a gage is bonded to a surface, it cannot be removed again without a very strong possibility of damage. For this reason, the gages supplied by SWRI had a much longer piece of elastomer than was required for the gage section. For calibration, they were bonded to the jaws of the calibration fixture (Figure 2-10) by the extra long extensions. The jaws of the fixture were then displaced a known amount and a reading of the gage resistance was taken for each displacement. Alternatively, the gage was connected in a bridge circuit, as shown in Figure 2-12, and then the bridge output signal was measured for the various displacements.

After completion of the calibration procedure, the extra lengths of elastomer were removed from the calibration jaws and then cut off the gage without impairing its performance in later operational tests.

If the elastomeric gage is used in a bridge circuit such as that shown in Figure 2-12, then the calibration output signals should be plotted as a function of strain for a fixed temperature, and the data should be plotted against temperature for fixed strain values. Typical data are shown in Figure 2-13.

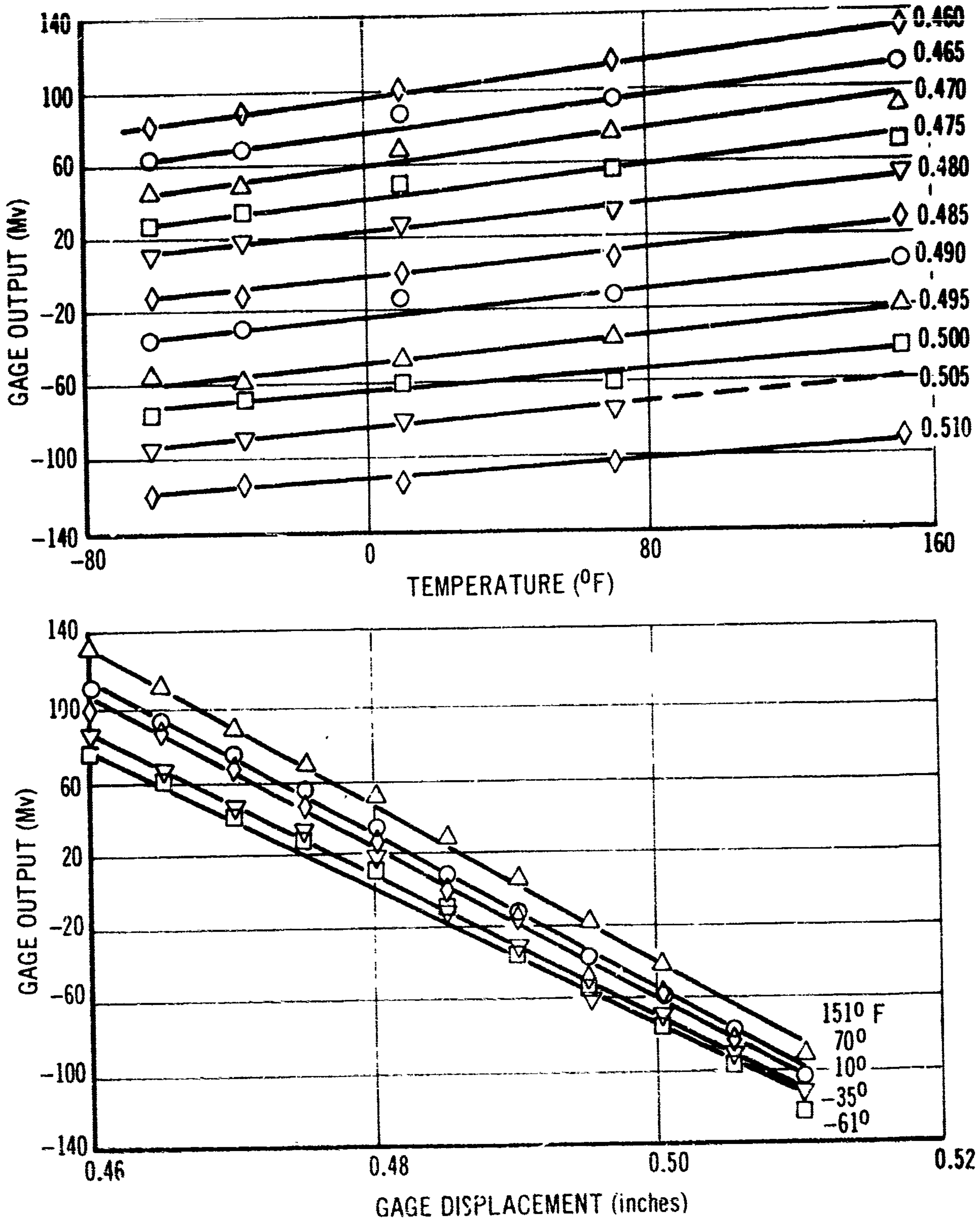


Figure 2-11 Clip Gage Calibration Data versus Temperature and Displacement

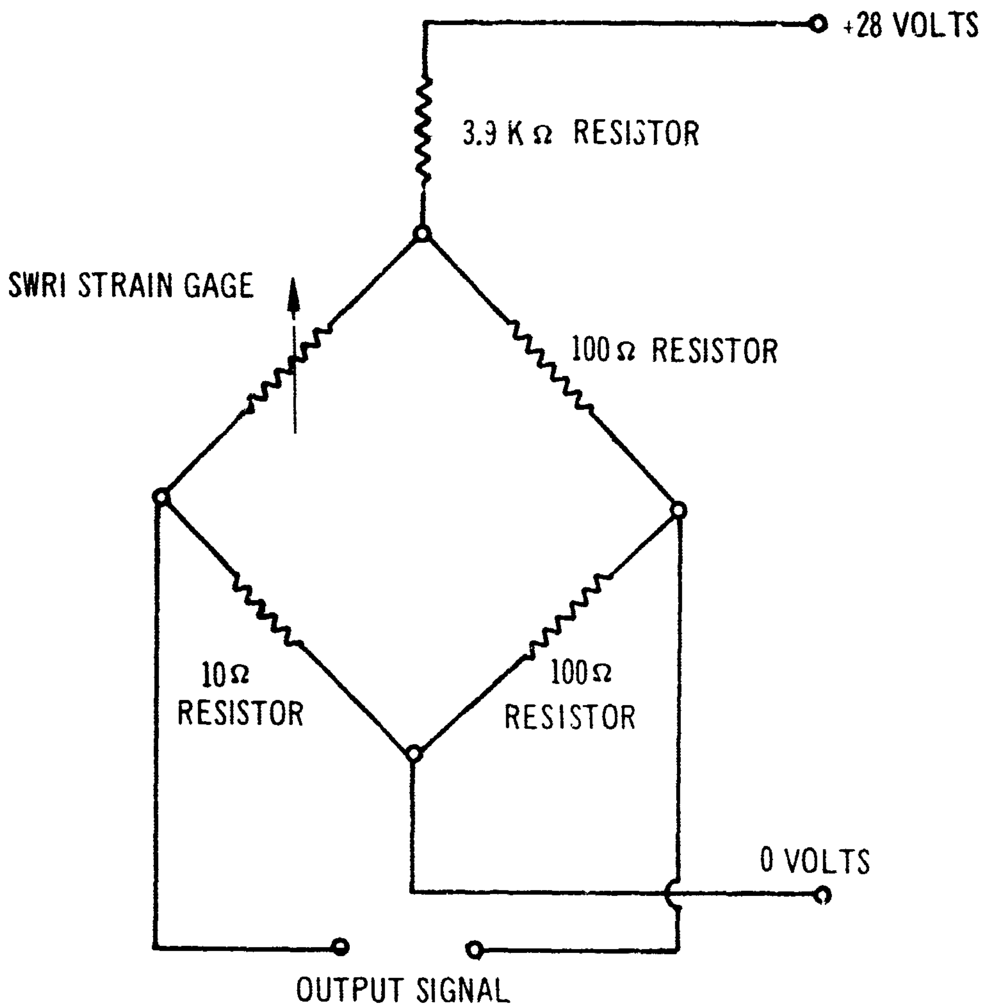
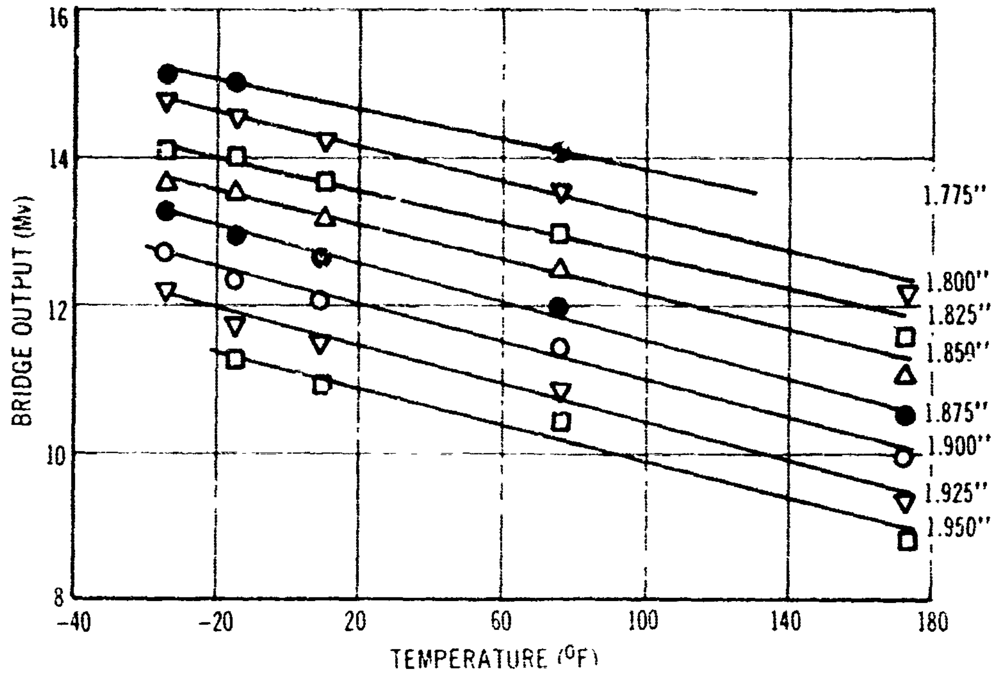
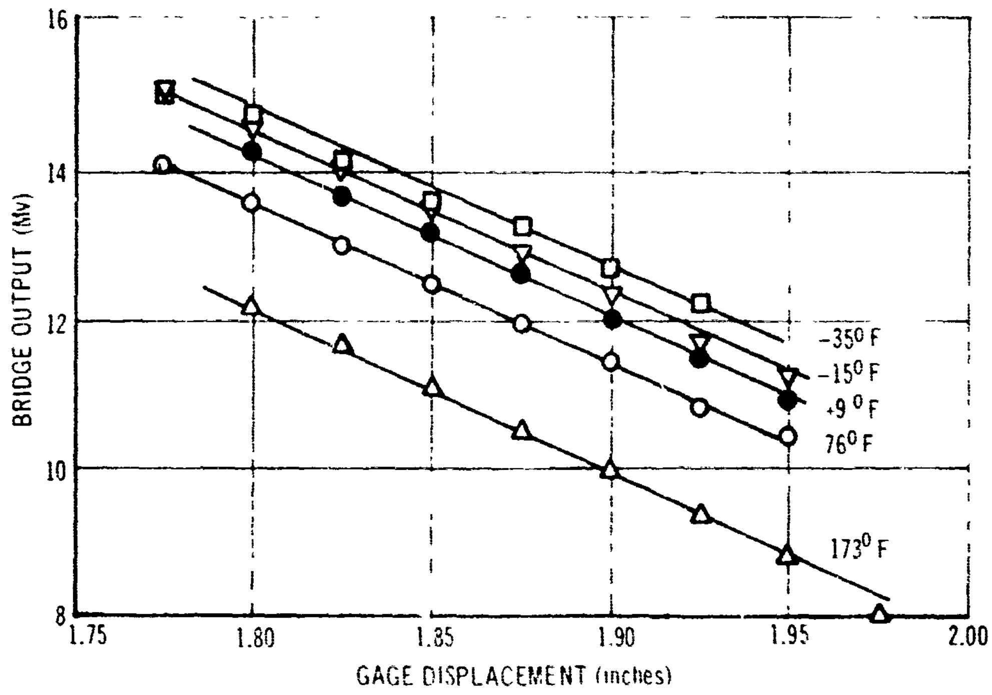


Figure 2-12 Bridge Circuit for Low Resistance SWRI Elastomeric Gages



Output versus Temperature



Output versus Displacement

Figure 2-13 SWRI Elastomeric Gage Output versus Temperature and Displacement

Alternatively, SWRI recommends the use of the gage resistance values in an equation of the type

$$\epsilon = \sqrt{\frac{R - C}{R_o - C}} - 1 .$$

where C is a constant supplied with the gage, and R_o is the gage resistance at a specified initial temperature.

2.3.4 Embedded Strain Gages

This type of device is probably the most difficult to calibrate properly without the risk of damaging it after calibration is completed. The reason for this problem is that the gages are calibrated in a shear test fixture such as that sketched in Figure 2-14. The shear gage is manufactured from a piece of cured propellant or elastomer of the type to be cast in the motor, or from a piece of inert simulated propellant if the safety hazard is judged too severe.

The shear gage is bonded to the central member of the chevron double overlap shear specimen, which may be wood or metal. The two outer members of the specimen are fixed in the correct location relative to the center member and propellant is cast into the specimen mold and cured.

After cure is complete, the shear test specimen is wired to an electrical board to form the gage bridge circuit(s) and the specimen is placed in a temperature conditioning box for calibration.

The specimen is mounted with the outer pieces attached firmly to the crosshead and with the center arm of the specimen rigidly attached to the load cell and the top of the testing machine.

Again, two calibrations are required, a thermal calibration and a strain calibration. In the thermal calibration the specimen is held fixed under zero strain conditions while the temperature is changed to a series of values corresponding to the desired operating range.

The strain calibration must be carried out at the various temperatures by applying strain increments and monitoring the gage output signal. This procedure is valid if the propellant or elastomer does not exhibit significant viscoelasticity, since the implicit assumption is made that there is no change in gage reading with time.

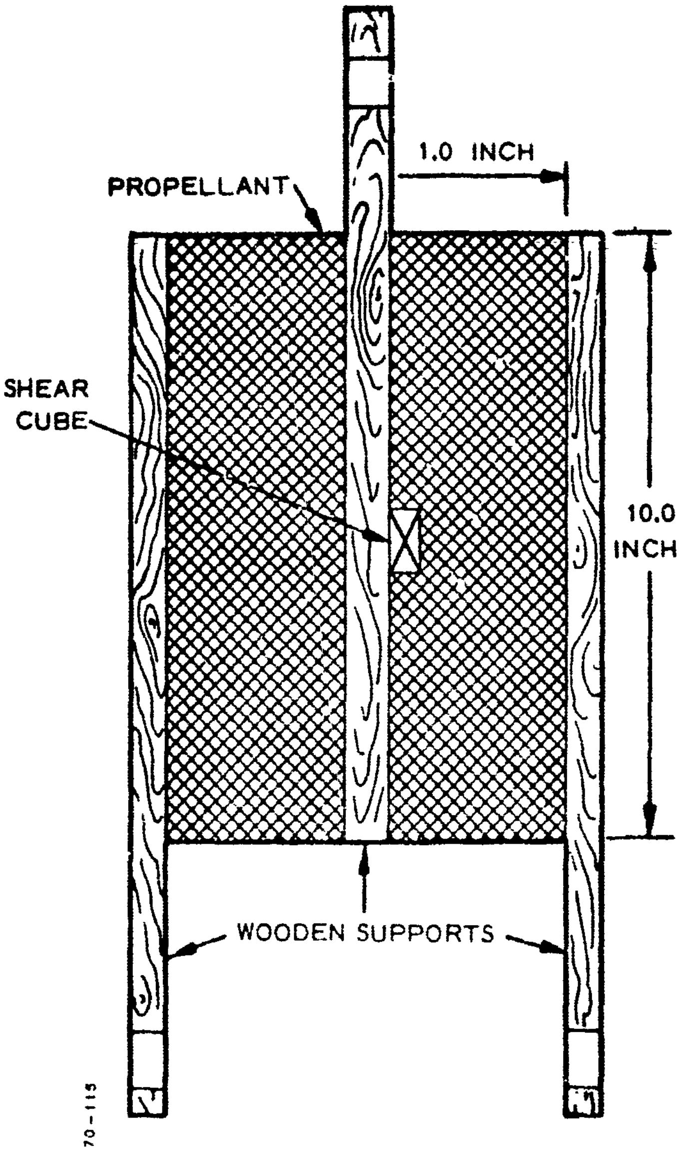


Figure 2-14 Shear Calibration Test Fixture

When the gage reading is observed to change with time, showing that the propellant is viscoelastic, then the calibration procedure must be changed to that suitable for a time-dependent process. The calibration technique used is the stress relaxation or constant strain type of test. A known strain increment is applied to the specimen by means of a rapid crosshead movement. The gage reading is then recorded for a period of 10 to 20 minutes as the stress in the specimen decays. Logarithmic time intervals should be used for the gage readings in a manner similar to the procedure adopted for a propellant stress relaxation test.

The constant strain tests should be repeated at the various temperatures of interest. The resulting data obtained will probably resemble that shown in Figure 2-15. These data curves may be translated along the log time axis to produce a master gage calibration curve as a function of reduced time. The data of Figure 2-15 have been treated in this manner in Figure 2-16, and the associated shift factor versus temperature data are given in Figure 2-17.

If the stress relaxation data for the propellant are obtained simultaneously with the gage calibration data, then a more accurate procedure may be used. A discussion of this approach is presented in Appendix A.

Briefly, the stress relaxation data are first shifted to produce a master stress relaxation modulus curve versus log reduced time. The gage data are then shifted by the shift factors obtained from the relaxation test data. In many instances this will result in a smooth gage calibration function curve but, in others, the individual temperature curves will be displaced as shown in Figure 2-18. To produce a smooth master gage calibration curve, it is necessary to shift the various temperature curves in a vertical direction, thereby producing the curve shown in Figure 2-19. The small shift factors required to make all the temperature curves align are plotted against temperature in Figure 2-20.

The vertical shift amounts to a correction for the change in sensitivity with temperature and is independent of time. The reasons for this vertical shift factor need not be discussed here. Suffice it to say that if the gage shows a marked change in sensitivity with temperature, perhaps due to poor temperature compensation, then a vertical shift factor will probably be required to bring the various temperature curves into alignment.

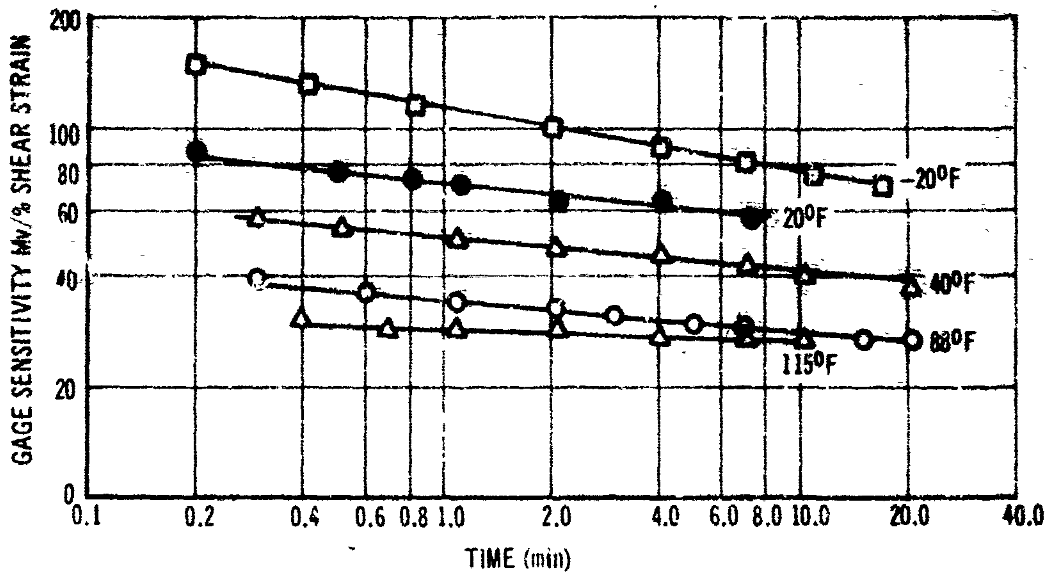


Figure 2-15 Constant Strain Test Data from Shear Cube

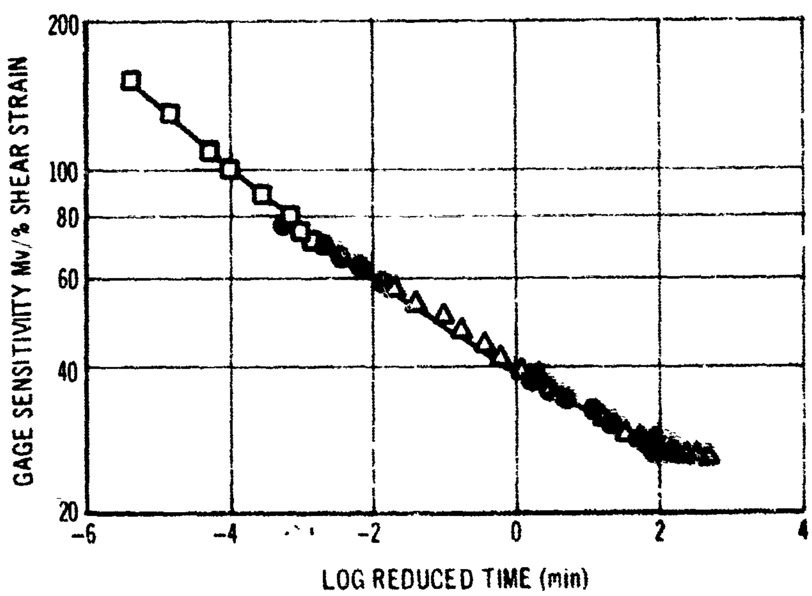


Figure 2-16 Shear Strain Sensitivity versus Log Reduced Time

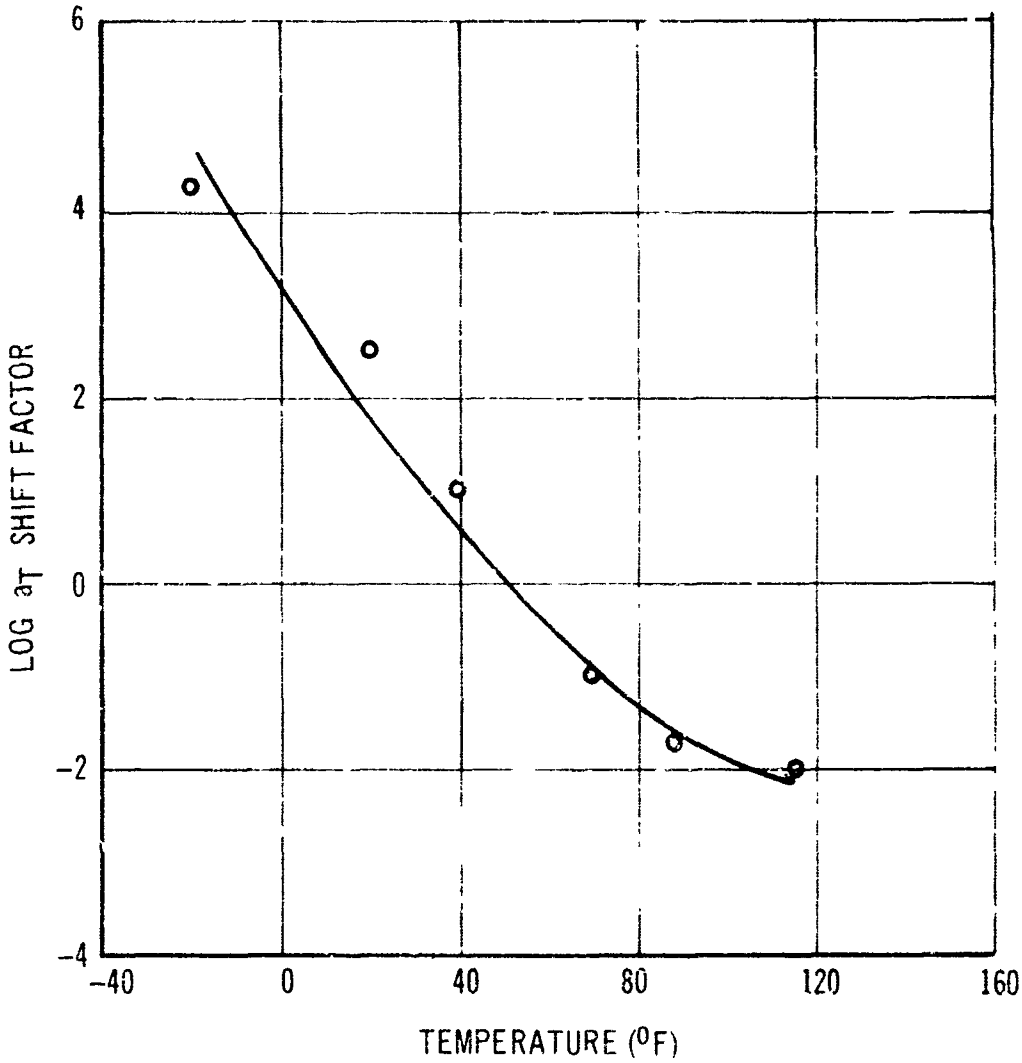


Figure 2-17 Log Shift Factors Log a_T versus Temperature

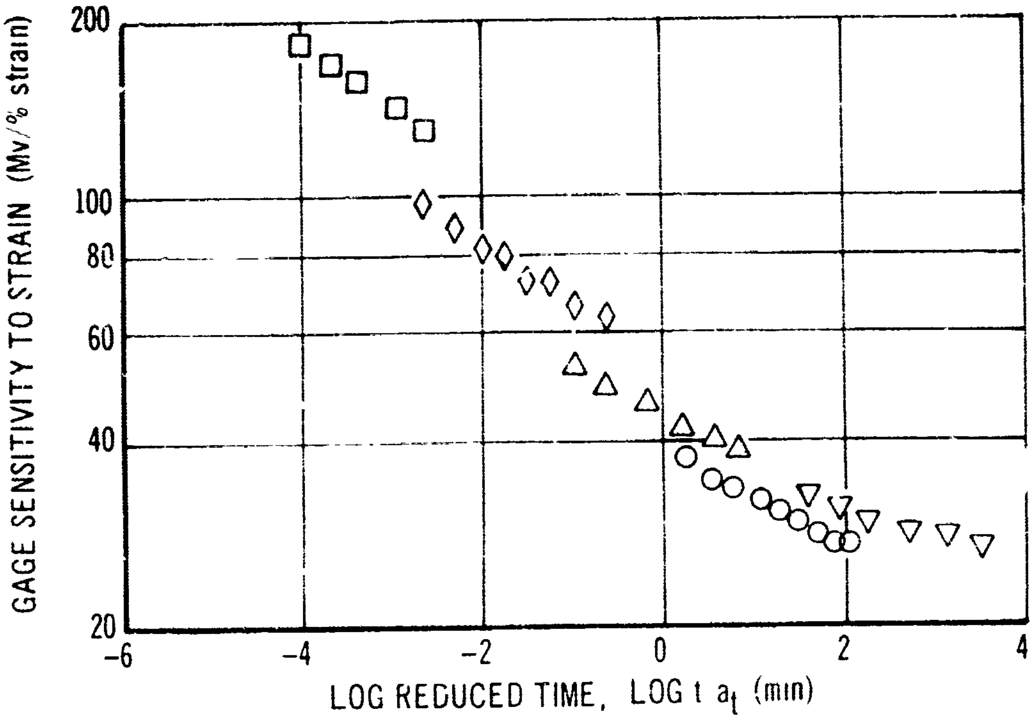


Figure 2-18 Shear Gage Sensitivity Data Shifted by Propellant Shift Factors

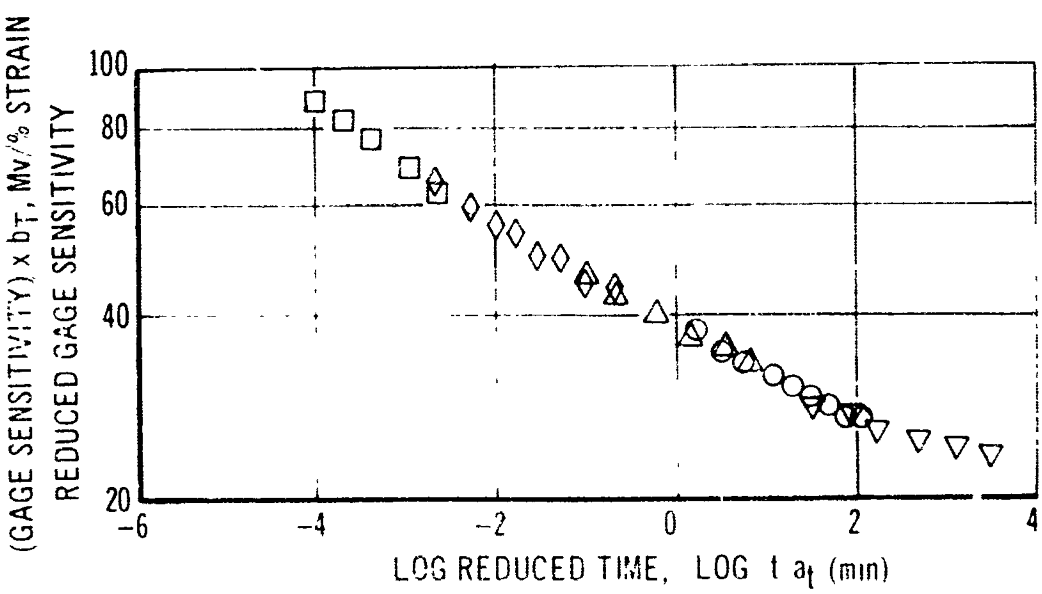


Figure 2-19 Shear Gage Sensitivity Data After Vertical Shift Applied

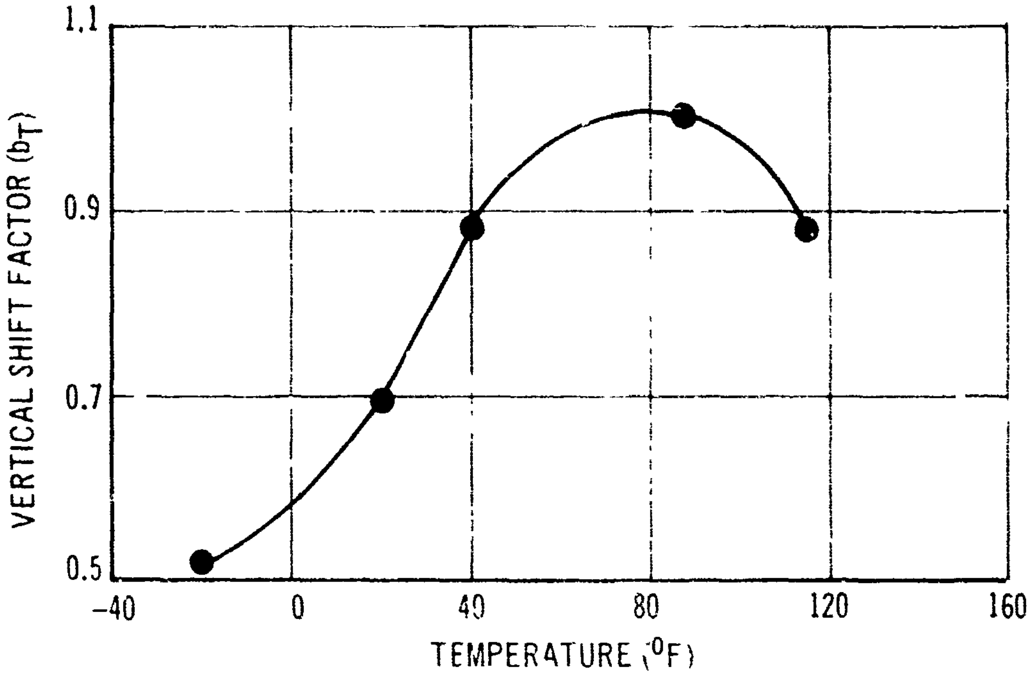


Figure 2-20 Vertical Shift Factors for Shear Gage Data

In addition to the shear calibration of the gages, it is usually necessary to determine the shear gage response to a normal strain so as to permit an assessment of the inherent errors in the shear gage output data. This calibration test is performed simply by rotating the specimen and gripping the wooden or metal edges in a pair of strip biaxial-type jaws. The specimen is then strained in a normal direction and gage readings are taken as in the shear tests. If a viscoelastic calibration is required for the shear tests, it will probably be necessary for the normal strain tests. Depending on the accuracy required from the shear gages, it may be necessary to perform a normal strain calibration at various temperatures throughout the range of interest. Conversely, it may be sufficient to determine cross sensitivity at, for example, ambient temperature and to assume that it remains constant at the various temperatures. The choice depends on the time available more than on any other criterion.

2.3.5 Moiré Grid Strain Measurement

The only requirement for calibration of a Moiré grid relates to the actual spacing of the grid lines. This spacing, of course, determines the number of fringes that will be obtained for a given relative displacement between the master grid and that on the propellant surface. It is essential that the line spacing be known precisely in order to determine accurately the surface strain.

The grid spacing may be measured accurately by means of a travelling microscope. Another method is to bond a small piece of the grid to one end of a uniaxial tensile test specimen and another small piece a known distance away, overlapping the first piece of grid. The specimen is then placed in a testing machine and pulled at a slow crosshead speed. As the specimen is strained, fringes will appear as the two grids alternately superpose. The spacing between the fringes is a measure of the grid line spacing, which can be determined from the known crosshead speed and the chart speed of the recorder.

2.4 INSTALLATION OF STRAIN GAGES

2.4.1 Surface Strain Gages

Conventional resistance strain gages for the measurement of surface strain, as in the wall of a motor case, are affixed to the surface by an epoxy resin adhesive after the surface has been carefully abraded and cleaned. The resin is then cured, after which the gages may be wired up. It is necessary to apply pressure to the gages while the adhesive cures and sets. Pressure may be applied by a weight if the surface is sufficiently flat. A piece of Teflon tape should be placed over the gage to prevent sticking of the weight. It may also be beneficial to make use of a piece of foam rubber on top of the Teflon, with the weight placed on top of the foam. This is useful for moderately curved or irregular surfaces.

For situations in which speed is essential and the range of temperatures is limited, the gages may be attached to the surface with Eastman Kodak 910 adhesive. This adhesive has the great advantage of curing very rapidly so that the gages can be used within minutes after applicatio- 'he adhesive cures so quickly that the gage may be held onto the surface by hand while cure takes place.

Probably the main precaution that should be taken is to properly clean the surface to which the gage is to be bonded. A solvent wash followed by a light sandblast is best. However, gages have been attached after a simple rubdown with emery cloth and a solvent wash. It should be remembered that the accuracy and repeatability of the gages will be determined to a large extent by how well they are attached to the substrate.

2.4.2 Clip-Type Surface Strain Gages

The problems of mounting this type of surface strain measuring gage were discussed in subsection 2.1.2. The severity of the environment to which the gages will be exposed will determine the type of mounting technique to be employed. For many applications, simple bonding of the gage tabs to the surface of the grain will be sufficient. For the more severe types of loading that may be encountered in flight, the use of pins, inserted in the grain, may be required.

Again it is imperative that the surface of the grain should be clean before either the pins or the tabs of the gage are bonded in place. The surface on which the gage is to be mounted should be wiped carefully with a solvent-dampened cloth to remove the wax coating usually found on the bore of a grain from contact with the mandrel during cure. Subsequently, the surface should be carefully roughened with sandpaper or emery cloth.

2.4.3 Elastomeric Surface Strain Gages

These gages are mounted in much the same way that resistance strain gages are bonded to the case surface. Surface preparation procedures, however, are more like those used to bond the clip gages in place.

The surface of the propellant grain should be cleaned with a solvent-dampened cloth and roughened with an abrasive before the elastomeric gage is bonded in place. For bonding the gage to the propellant surface, the best type of adhesive has proved to be a liner material, used normally for bonding propellant to the case wall during cure. Some method of maintaining a pressure on the gages must be used during the time that the liner takes to cure, usually 24 hours.

2.4.4 Embedded Strain Gages

Embedded strain gages, such as the shear cube, are generally used at the case-grain interface. It must first be determined whether or not the gage is to be placed inside the insulation, which is the most common approach. The alternative is to bond the gage to the case wall, which is easier from the point of view of installing the lead wires to the gage. In most instances, the best approach is to prepare the case as normal, including the insulation and any boots or flaps that might be employed. The strain gages, consisting of the propellant or elastomeric cube embedded in a matrix of the calibration specimen material, may then be trimmed so that they fit snugly at the desired locations inside the insulated motor case. The gages are usually bonded in place with the liner material. Some means of holding them in place during liner cure is required. The lead wires may be attached to the insulation with liner material at the same time that the gage is being bonded in place.

A problem that may be encountered in some motors is that of bringing the gage lead-out wires through the flap or boot and then to a suitable through-the-case exit terminal. No general rules can be made for this type of problem, because every motor design is different and the specific solution to the problem has to be found for the particular combination of factors at hand.

After the gages are properly installed in the motor case, they should be wired to the circuit board and tested to ensure that they are still working. If this test is satisfactory, the gages may be lined, together with the interior of the motor case, in preparation for propellant casting.

Section 3
STRESS MEASUREMENT

3.1 TYPES OF TRANSDUCER

3.1.1 Transducer Classification

Stress transducers may be classified as either normal stress or shear stress measuring devices. The requirements for these two types of stress transducer are quite different, as will be shown later in this section.

Another possible method of classification depends upon the physical aspects of the application, i. e., whether the gage must measure stress through a hole in the motor case wall (the through-the-case type) or can be mounted inside the case (the miniature diaphragm type).

Both classifications will be used in the following sections, in a subordinate relationship. The two main classifications are (1) the normal stress and (2) the shear stress devices, each of which is further subclassified as (a) through-the-case or (b) internally embedded.

3.1.2 Through-the-Case Normal Stress Transducers

Piston type. This class of instrument has been used extensively for fluid pressure measurements (Ref 13). Essential features are illustrated in Figure 3-1. For rocket motor application, a hole is drilled in the motor case. A steel plug, attached to the gage section of the transducer, is inserted in the hole flush with the inner case surface. The strain-gaged element is attached to a stiff housing, which is attached rigidly to the outer surface of the case. Any force applied to the steel plug causes a slight deflection of the strain-gaged element. This deflection is interpreted as a stress across the plug diameter. By making use of small, sensitive, semiconductive strain gages, the compliance of the strain gage section can be kept to an extremely low value (dependent upon the required gage sensitivity). Transducers of this type can be designed so that they exhibit virtually no change in properties over a wide temperature range. They also have an advantage in that local perturbations in the grain stress field are kept to a negligible level.

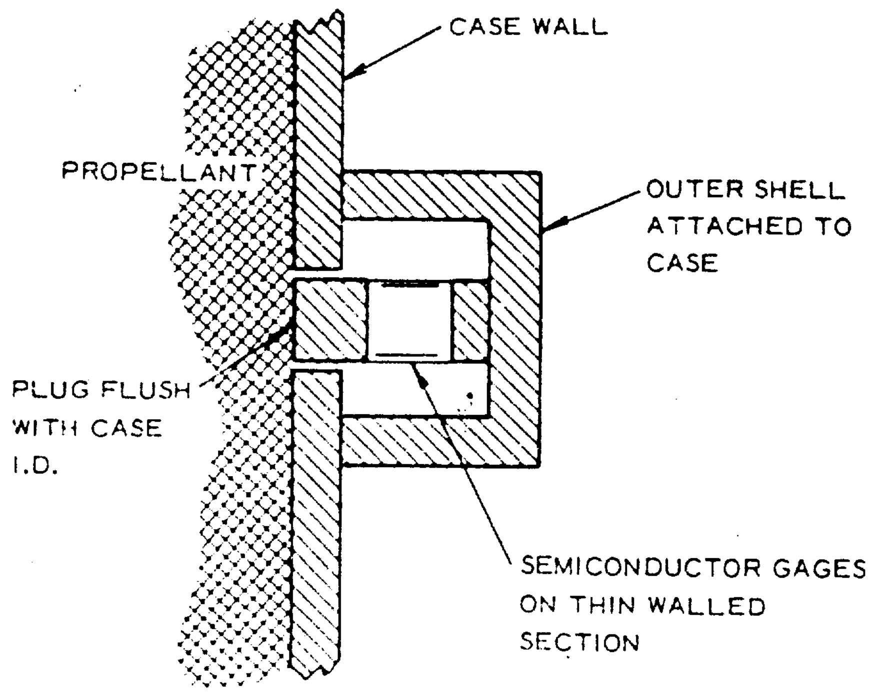


Figure 3-1 Through-the-Case Stress Gage Schematic

Figure 3-2 shows the details of the Rocketdyne through-the-case normal stress gage, which has been used successfully in a number of programs, including the First Stage Minuteman Motor Program (Ref 4). These gages are usually operated from a low, constant voltage supply (4.0 volts). With this supply voltage, their output is approximately 0.15 mv/psi across the whole temperature range of interest.

Diaphragm type. Recently, Konigsberg Instruments developed a case-mounting through-the-case version of their P-14 diaphragm stress sensor. A sketch of the device is shown in Figure 3-3. It will be noted that the transducer screws into the case wall, exposing the sensitive diaphragm with its semiconductor strain gage elements to the propellant (or insulation) material.

This particular transducer, with a range of 50 psi, was developed especially for the instrumentation of the AFRPL-sponsored First Stage Minuteman Motor Program (Ref 4). The device combined the sensitivity of the diaphragm sensors with the through-the-case configuration required in this program. The gages performed well during operational tests and proved capable of resolving small dynamic stress levels of the order of 0.5 psi.

The through-the-case Konigsberg diaphragm gage may be connected as two independent half-bridges or as a single full-bridge circuit. They were connected as a single full-bridge circuit for the Minuteman testing program and were operated with a bridge voltage of approximately 4.0, from a 28-volt supply. Gage sensitivity varies between 2 and 4 mv/psi over the temperature range of 20 to 135^{0}F.

3.1.3 Embedded Miniature Diaphragm Normal Stress Transducers

The miniature diaphragm transducer was developed for fluid or gaseous pressure measurements. A schematic of the device is shown in Figure 3-4. It consists of a circular metallic diaphragm supported by a rigid metal ring with a metal back sealing the cavity. Semiconductor strain gages are mounted on the diaphragm to measure its deflection under pressure. By making use of both the compressive stresses and the tensile stresses generated during flexing of the diaphragm, a temperature-compensated gage is produced. The diaphragm pressure transducer was developed at LPC for

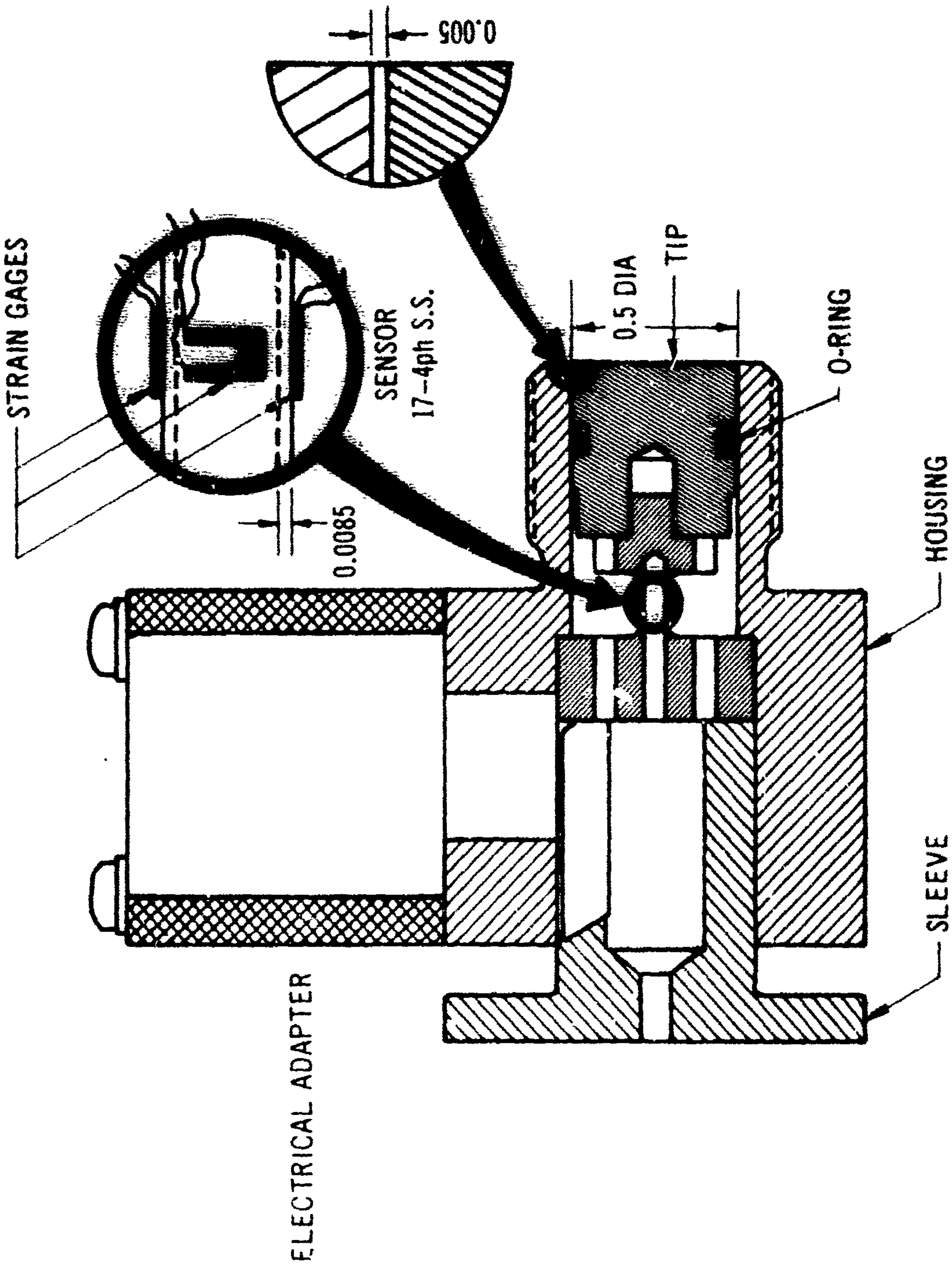


Figure 3-2 Rocketdyne's Through-the-Case Normal Stress, Piston Type Transducer

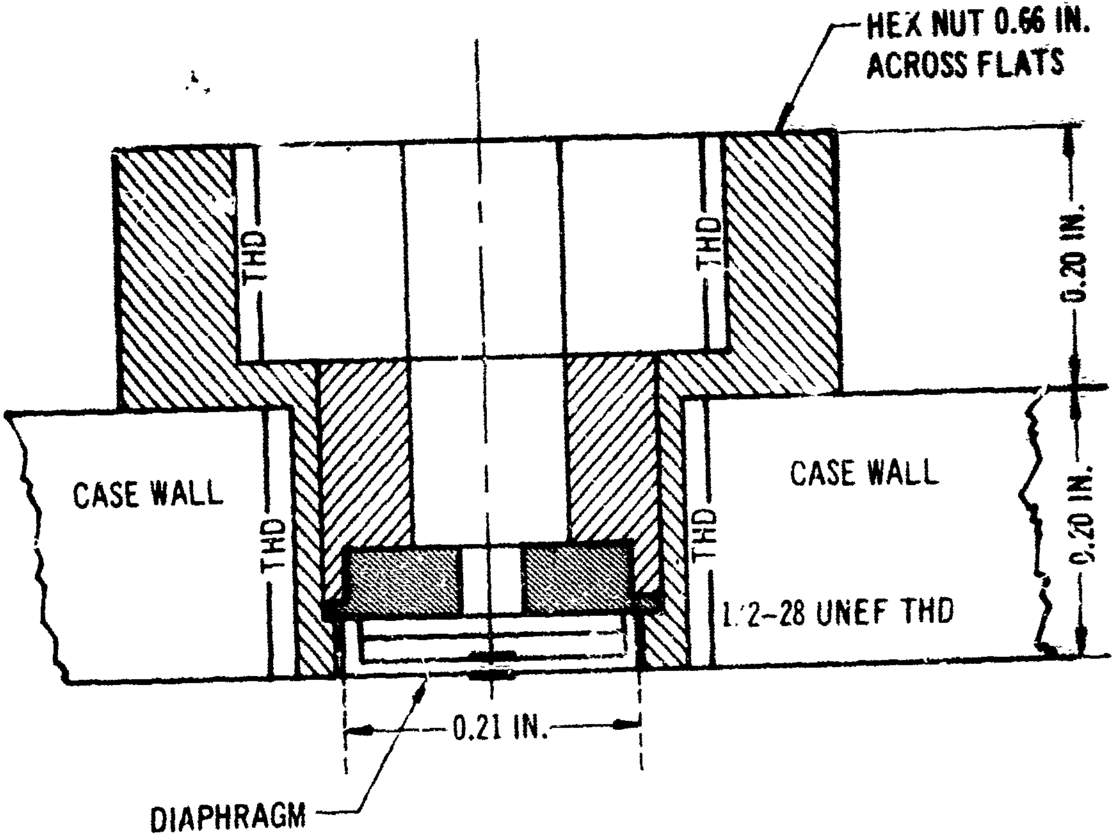
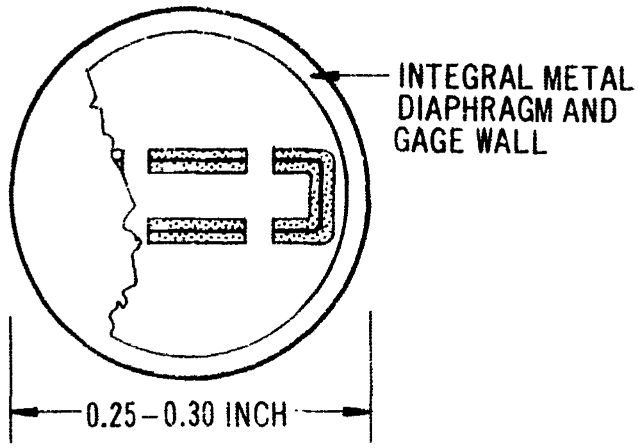


Figure 3-3 Konigsberg's Through-the-Case Normal Stress Diaphragm-Type Transducer



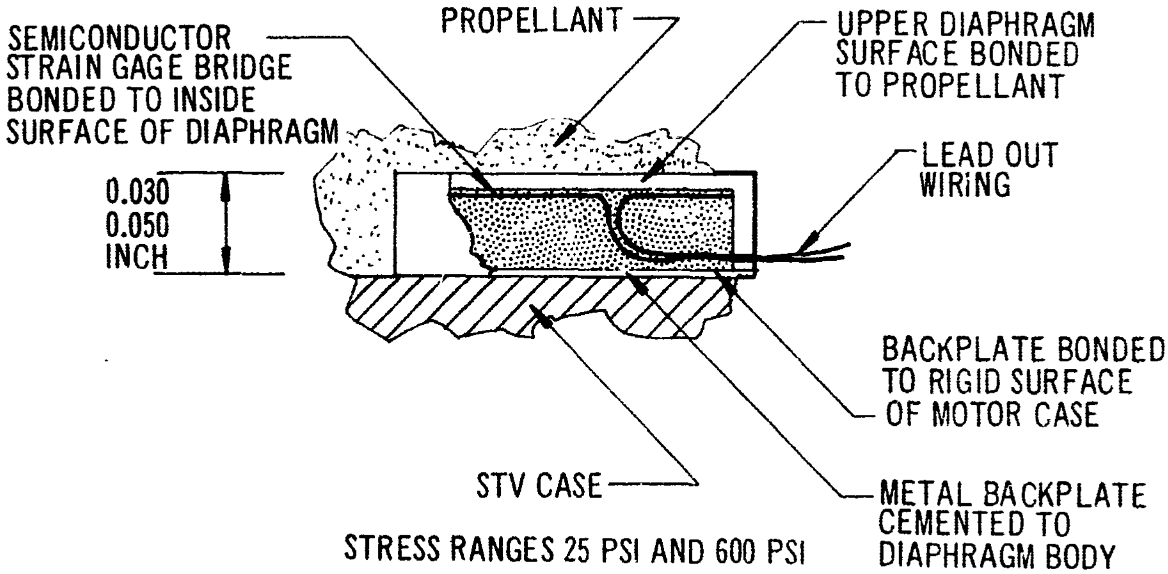


Figure 3-4 Miniature Diaphragm Gage Schematic

use as an interface normal stress sensor. The earliest device used was the Electro Optical Systems (EOS) Model No. 1017-0023 (Figure 3-5), designed for biological pressure measurements up to 25 psi.

Preliminary tests and analysis revealed that this gage showed a considerable loss in sensitivity when used with propellant at low temperatures, as shown in Figure 3-6. To overcome this defect, the much stiffer 600-psi transducer (EOS Model No. 1070-0024), also shown in Figure 3-5, was designed. Although the increased diaphragm stiffness prevented the loss in gage response at low temperature (Figure 3-6), overall accuracy was degraded because the inherent thermal errors were now of an order of magnitude similar to that of the output signal caused by stresses.

Later in the STV program, a compromise 150-psi range diaphragm transducer (EOS Model No. 1003-0200), illustrated in Figure 3-5, was developed. The limitations of this gage have not been completely explored. It has shown virtually no loss in sensitivity when used with propellant at temperatures as low as -45^{0}F (Figure 3-6). Furthermore, the sensitivity is such that the response to stress is much greater than the thermal error signal.

Evaluation of the analytical work of Professors Pister and Fitzgerald (Appendix A) indicated that the basic diaphragm transducer could be improved by making use of only the central portion of the diaphragm. It appeared that the changes in propellant modulus had little influence on the curvature at the middle of the diaphragm, but made great changes in the curvature toward the edge. Thus, the latest transducer design, shown in Figure 3-5, incorporated semiconductor strain gages on the outer and inner surfaces of the diaphragm, thereby eliminating the temperature-compensating peripheral elements. In addition, the gage shoulder was stiffened to prevent rotation under stress and the outer edge was chamfered to provide a less severe discontinuity between the gage and the propellant.

The new 150-psi gage was designed and manufactured by Konigsberg Instruments, Pasadena, and is designated as type P-14.

Elimination of the peripheral strain elements allowed a given transducer to be designed to twice the pressure (for a specified limiting strain value), so that the 150-psi device became a 300-psi capacity transducer. In addition, the use of two gages on the inner diaphragm surface and two on the

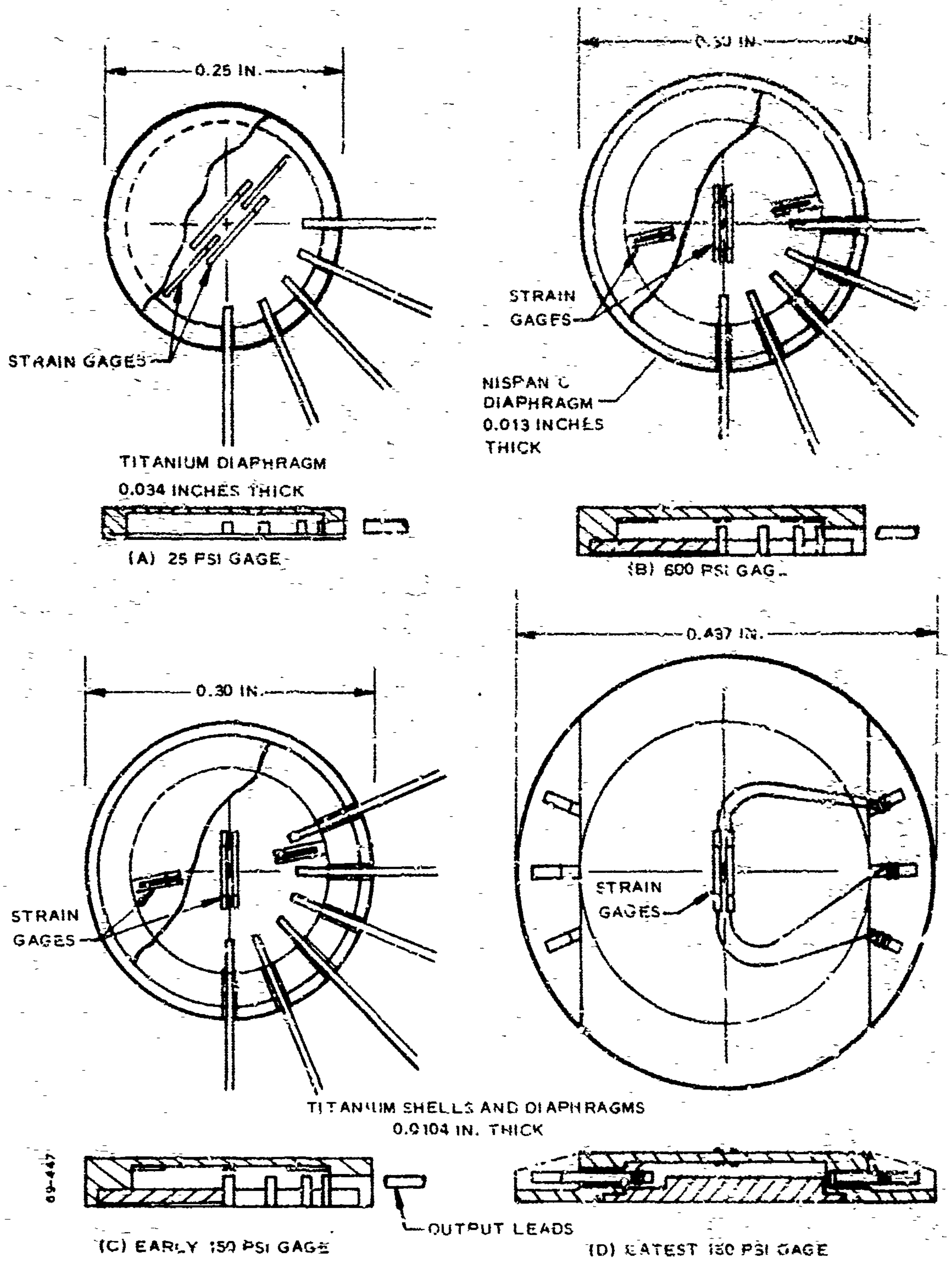


Figure 3-5 Diaphragm Gages Used in STV Program

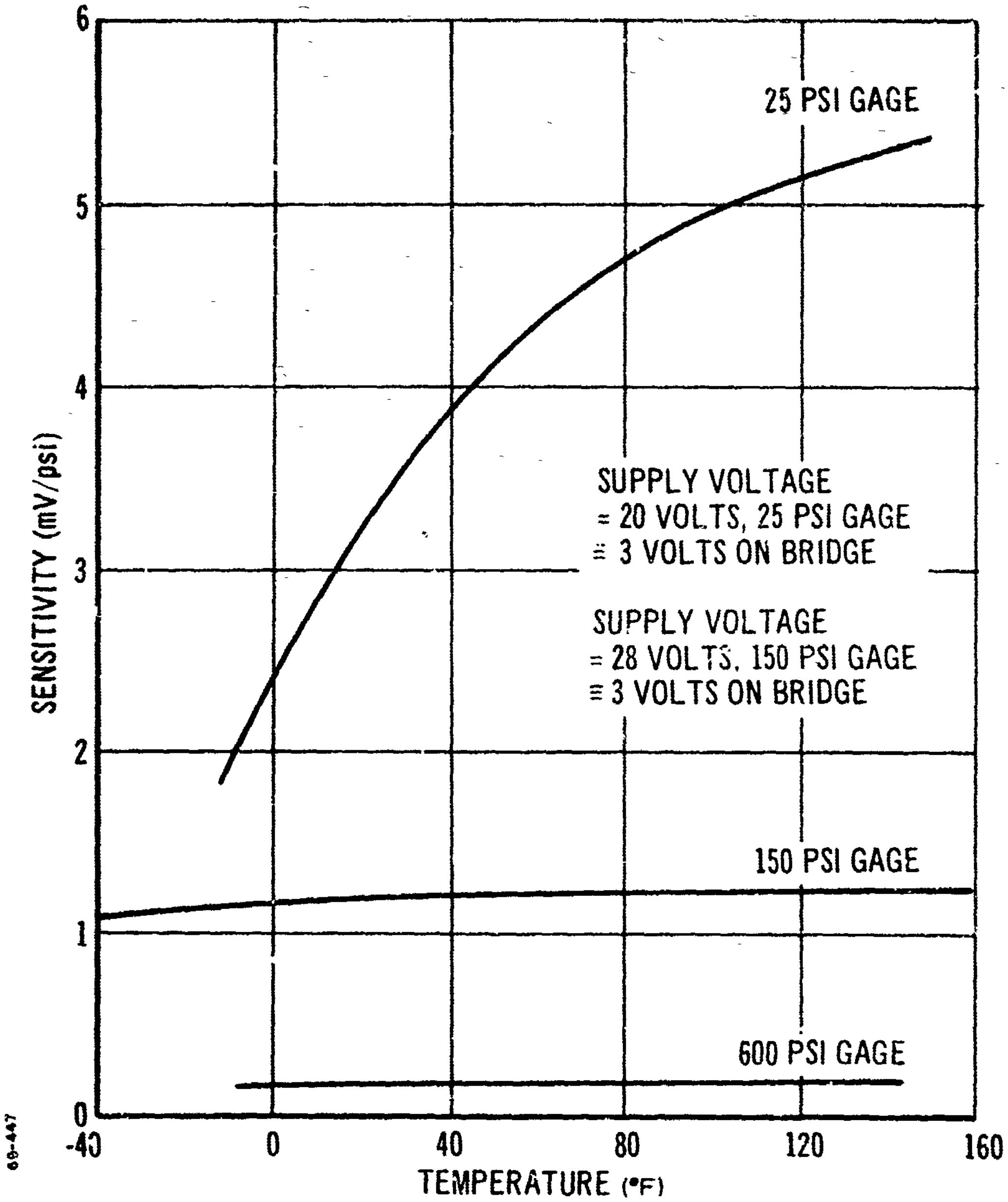


Figure 3-6 Diaphragm Gage Response versus Temperature

outer surface gave a sensor with almost twice the sensitivity of the earlier 150-psi transducers. These overall improvements result in a normal stress transducer having greatly increased sensitivity, and increased overload capacity, as well as reduced thermal error, hysteresis, and nonlinearity of response. The externally mounted semiconductor strain gage elements are possibly detrimental to use of the instrument as a commercial pressure gage, but they improve its performance in a propellant rocket motor.

This new type of 150-psi diaphragm transducer was evaluated during the STV and Bomb Dummy Unit programs at LPC. It was also evaluated and compared with piston-type, through-the-case transducers in the Transducer Evaluation Program at Rocketdyne (Ref 1, 2, and 3).

Experience with these gages suggests that they can measure stresses to within ±1 psi, or within ±2 percent of the reading under isothermal conditions. The error band increases to about ±10 percent of the reading when thermal stresses are considered.

During failure tests of an STV, several of the older type of 150-psi gages were subjected to pressure levels up to 1000 psi. They all functioned well during this severe test and at least one of them was still operational after the STV had catastrophically blown up at 1000 psi.

3.1.4 Through-the-Case Shear Stress Transducers

The piston type of through-the-case gage responds to both normal and shear loads through stretching and bending of its strain-gaged column. The shaft bending output is normally eliminated from the instrument reading through proper Wheatstone bridge circuits.

A through-the-case transducer was developed by Rocketdyne (Ref 3) for measuring the shear stress at a propellant-case interface. Figure 3-7 illustrates the essential features of the device. The shear stress is sensed by semiconductor gages attached to the sensor arms of the shear stress plate. Application of a shear load to the piston deflects the shear arms by a small amount and this deflection is monitored by the sensitive gages. In its original form the gage was designed to measure normal as well as shear stress at a given interface point. Design complexity and the availability of alternate normal stress sensors led to the revised transducer shown in Figure 3-8. The three sensor arms of the earlier model were replaced by

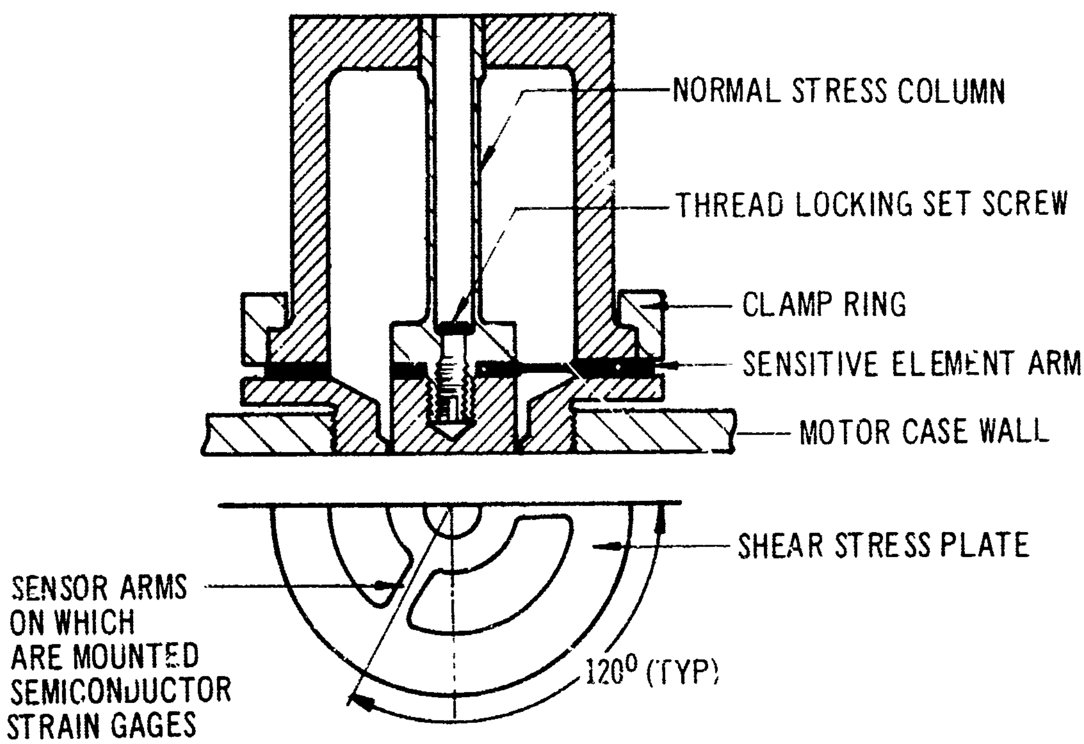


Figure 3-7 Prototype Through-the-Case Shear Stress Transducer

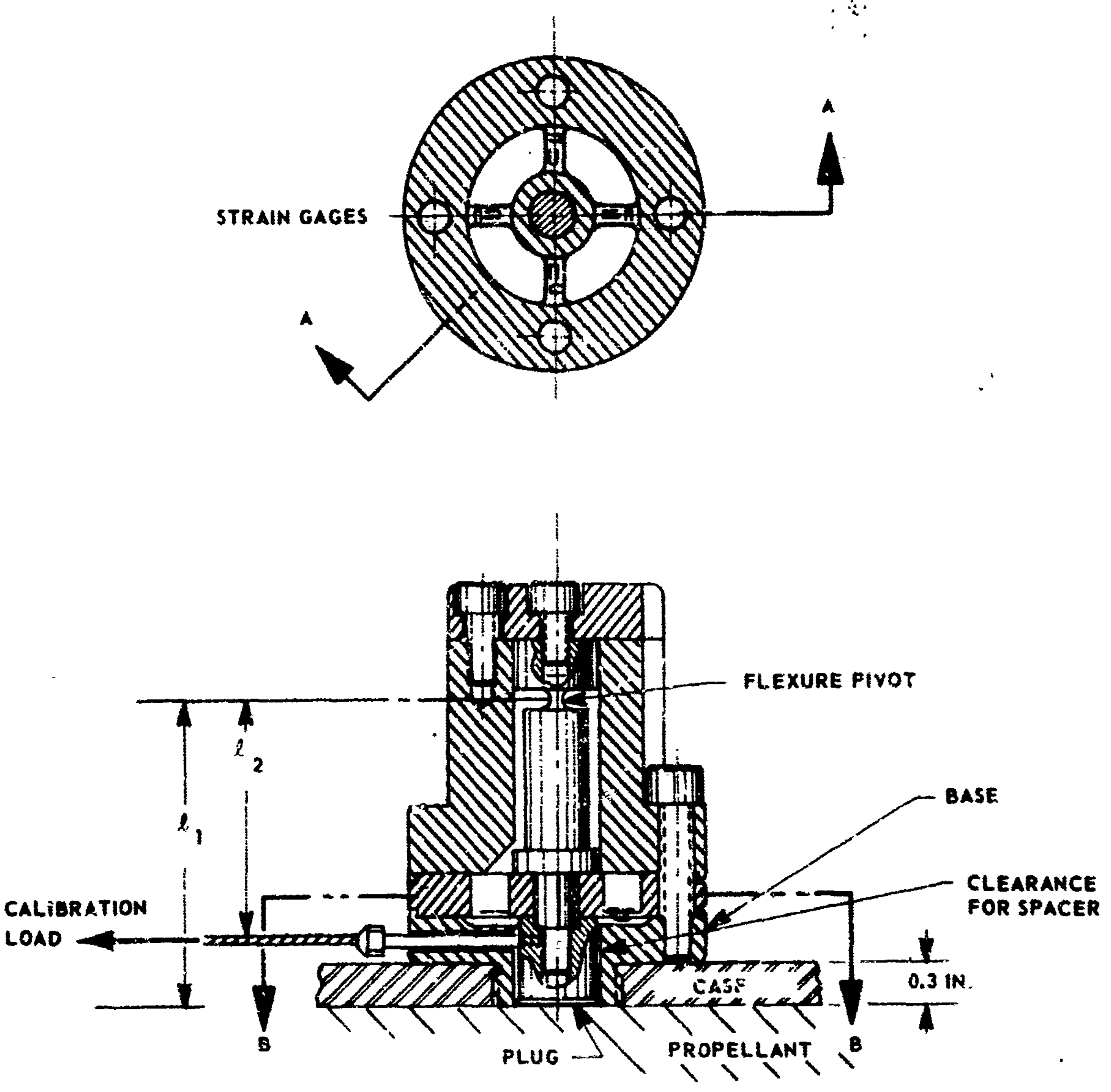


Figure 3-8 Rocketdyne's Modified Four-Web Through-the-Case Shear Stress Transducer

four arms. By arranging the semiconductor gages attached to the arms in the bridge circuits shown in Figure 3-9, independent readings are obtained for the shear stress components at right angles to each other. The stiffness of the shear stress gage is such that only very small signals are obtained. This, however, is not a serious problem as long as the noise level is kept to a low value.

The through-the-case shear transducers were used in the instrumented First Stage Minuteman Program (Ref 4), and gave good data at very low stress levels. By using a bridge voltage of 15 volts, a gage sensitivity of 0.20 mv/psi was obtained from the through-the-case shear gages.

3.1.5 Interfacial Case-Grain Shear Stress Transducers

The various types of embedded shear strain transducer discussed in subsection 2.1.4 may also be used to measure shear stress instead of strain.

The difference between a stress transducer and a strain transducer is discussed in more detail in Appendix A, but in this context it should be noted that the embedded gages containing rigid inclusions are neither perfect stress transducers nor perfect strain transducers. A perfect embedded shear strain transducer would deform with the propellant and would not modify the local stress field. A perfect interfacial stress transducer would respond to the applied stress rather than the deformation and again would not modify the local stress/strain fields.

Under many loading conditions the shear transducers will give good data when calibrated in terms of shear stress. The calibration technique is, therefore, the primary method of determining whether a transducer will respond to strain or to stress. The inherent limitations of the devices will determine how well they will operate as a stress- or a strain-measuring transducer.

3.2 APPLICATIONS FOR STRESS TRANSDUCERS

3.2.1 Through-the-Case Normal and Shear Stress Transducers

Clearly, the main application for the through-the-case type of transducer is for static or dynamic stress measurement at an interface. The units are designed to be attached to a rigid structure, such as the motor case wall, and their probe tip fits through a clearance hole in the case wall.

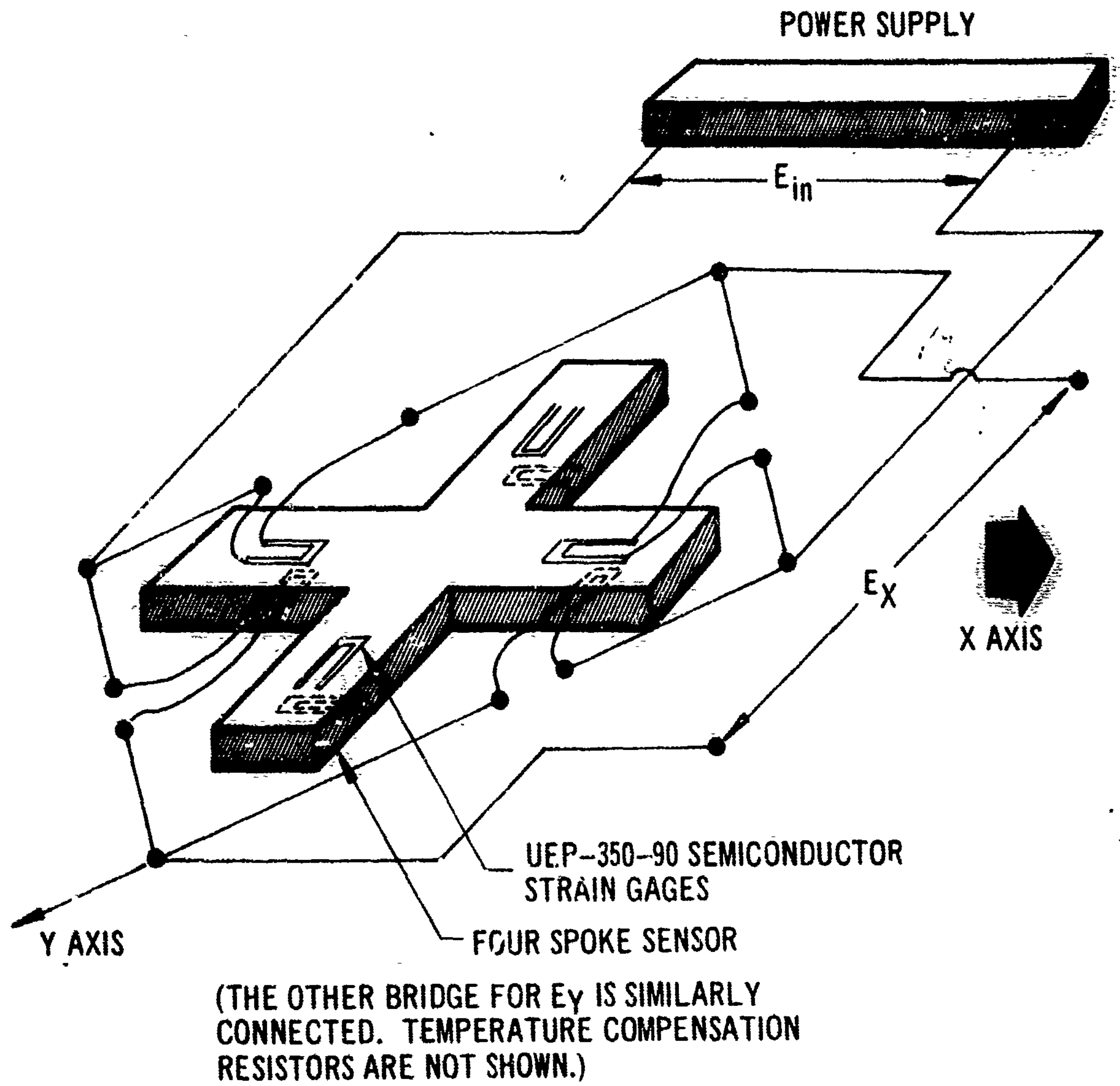


Figure 3-9 Bridge Schematic, Through-the-Case Shear Stress Transducer

These transducers have also been used for specialized testing, e.g., measuring the stress at the center of the platens of a poker-chip test specimen, the transducer being mounted on the rigid platen and the gaged-probe tip fitting through a clearance hole in the platen.

Methods of attaching and mounting these gages are dealt with at greater length in a later section of this report.

3.2.2 Miniature Diaphragm Normal Stress Transducers

These devices are somewhat more versatile than the through-the-case type of transducer. They may be used at a propellant-case interface, and in fact most of their applications have been at such locations. However, they may also be used inside the propellant grain, if required, and recent tests have demonstrated that they can produce excellent data under such operating conditions. They can be shown to be insensitive to all components of the stress field, except that normal to the surface of the diaphragm they are not influenced by the shear stress component. Thus they may be used in regions of high shear without losing their accuracy. The presently available devices have a diaphragm size of about 0.25 inch, which means they are not well suited to the measurement of normal stresses in regions of high stress gradient. There is no particular difficulty associated with the manufacture of a smaller-diaphragm transducer, because biomedical pressure sensors with a diameter of 0.10 inch are routinely made by competent manufacturers, including Konigsberg Instruments. No special version has been developed as yet for the particular requirements associated with embedding in propellant grains.

High pressure versions of the Konigsberg P-14 series of miniature diaphragm transducers may readily be made. A 3000-psi device has already been used for the measurement of small pressure gradients in a motor under firing conditions.

The diaphragm-type stress sensors are not well suited to the measurement of step-type pressure pulses or shock waves. The relatively limp diaphragm may attenuate and modify the shape of a very-high-rate wave front so that the transducer output signal may bear little resemblance to the input waveform.

They can, however, be used to measure moderate frequency cyclic data (up to 2000 hz) with acceptable accuracy. (An exact upper frequency limit cannot be specified without a knowledge of the particular test requirements.) Tests at LPC during the STV program showed that several of the devices would give good data at up to 2000 Hz, although there is a possibility of obtaining a resonance in the system at the higher frequencies.

3.2.3 Interfacial or Embedded Shear Stress Transducers

The devices illustrated in Figure 2-6 may be used as shear stress measuring transducers, as discussed earlier. They are clearly suited to the measurement of interfacial shear stresses and most of their use to date has been at an interface. Again, however, there is no real reason why this type of transducer is limited in application to the case-grain interface. With proper calibration, shear transducers may be employed at any worthwhile location within a grain. They should not be used in their present form at grain end terminations or regions of high normal stresses and high stress gradients. This is unfortunate because these are the very locations where it would be particularly useful to monitor shear stresses. However, it is a fact that there is a cross-sensitivity in the shear cube that amounts to approximately 10 percent. This means that the gage connected as a shear transducer will nevertheless give an output signal when a normal stress is applied to any of the cube faces, and the magnitude of this output signal will correspond to approximately 10 percent of the applied normal stress considered as a shear stress.

At first glance it would appear that the transducer with a cross-sensitivity of only 10 percent is reasonably good, and this is true. However, if the transducer is used in situations where the normal stress is an order of magnitude greater than the shear stress, for instance at the center of a grain, then the effects of the normal stress components will be as great as those produced by the shear stresses. This will result in very poor accuracy in the measurement of the snear stress component.

Embedded or interfacial shear stress measuring transducers should for this reason be limited to situations where the primary stress component will be shear and where only a small normal stress will occur.

The embedded type of shear stress transducer has given particularly good data under dynamic conditions. Several of the gages were used to measure interfacial shear stresses under vibration conditions with excellent results. The devices have also been used to measure relatively high-rate shear stresses (millisecond range, not microsecond) in motors under firing conditions, and they have shown compressibility effects in the grain, which had not been anticipated on the basis of the (incompressible) analysis.

The recent vibration tests on the shear cubes in the LPC STV program showed that the transducers would operate satisfactorily at frequencies up to 1000 Hz, under most situations. They did show the expected loss in response at the higher frequencies.

3.3 CALIBRATION TECHNIQUES FOR STRESS TRANSDUCERS

3.3.1 Approach

The calibration of a stress measuring transducer is, in general, more complex than the calibration of a strain gage, as discussed in more detail in Appendix A.

Because of the imperfections inherent in all available stress measuring devices, the calibration procedure must consider the entire system including the transducer, any case wall to which it is bonded, and the propellant that surrounds the transducer. It will be seen, therefore, that the device which up to this point has been regarded as a transducer, now becomes merely a sensor in a complex interacting system. The sensor readings have no real meaning except when interpreted in relation to overall system components. Once again, for a more comprehensive discussion of this complex topic the reader is referred to Appendix A.

In one respect the procedure for calibrating a strain gage is the same as that of a stress gage: The changes in gage output for both thermal variations and mechanical loading variations have to be examined.

3.3.2 Gage Calibration Fixtures

Determination of the experimental gage-propellant interaction, i.e., the calibration of the gage-propellant system, is best carried out in special test fixtures such as the uniaxial device illustrated in Figure 3-10, or the

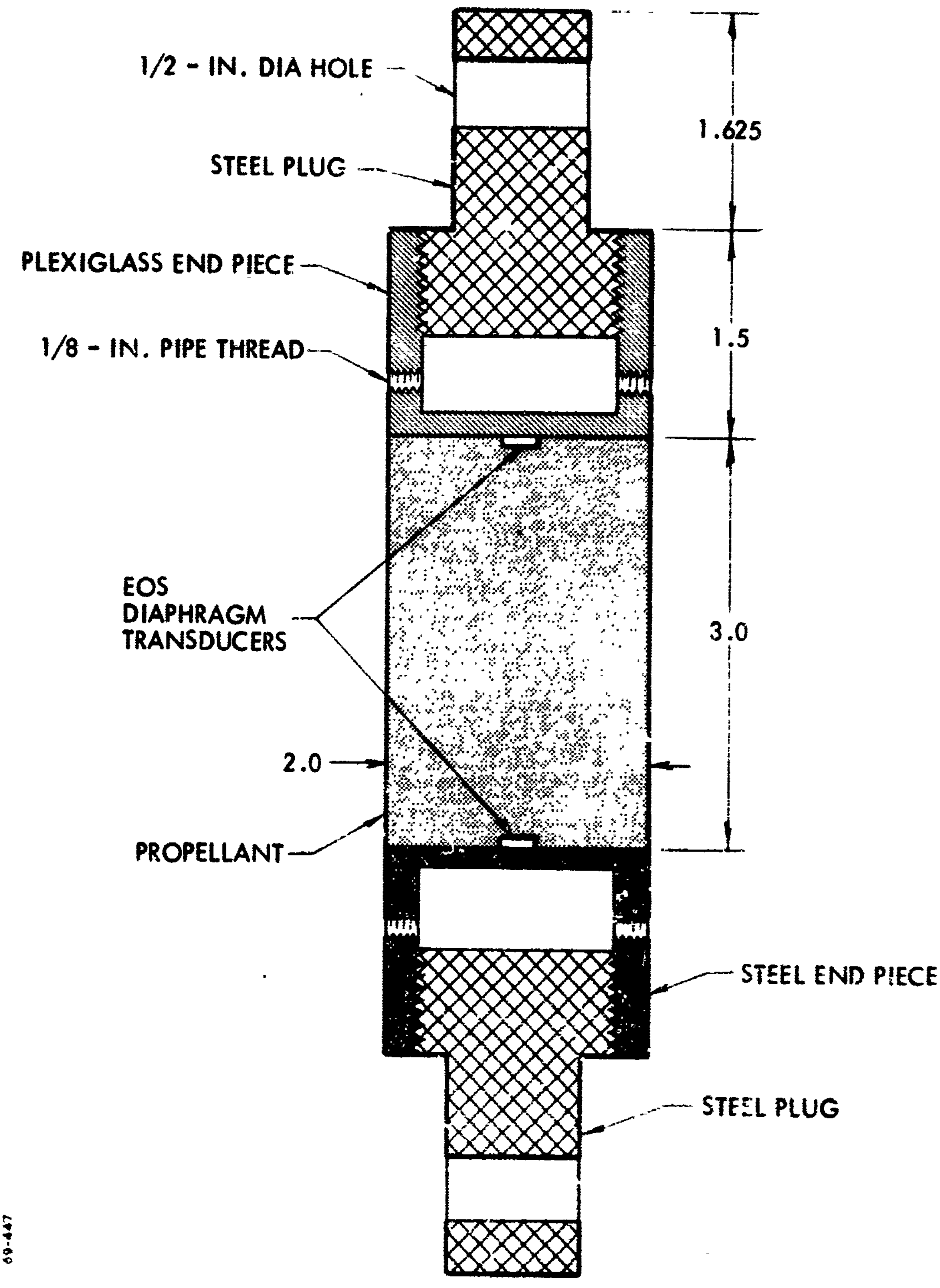


Figure 3-10 Uniaxial Calibration Test Fixture

simple shear device shown in Figure 3-11. In considering the design of calibration text fixtures, the most important point is that the stress distribution should be as simple as possible and amenable to analysis. Furthermore, the size of the fixture should be such that the gage is small in comparison with the test fixture.

Figure 3-12 shows a schematic of a uniaxial text fixture containing a gage, and shows the "zone of influence" of the gage. This is the region in which the test fixture stress distribution is significantly changed by the gage; it extends for about 3 gage radii from the center of the gage. Beyond this zone of influence the propellant stress distribution is virtually unchanged by the gage. In a satisfactory calibration test fixture the zone of influence should be well within the test fixture, i.e., no part of the zone of influence of the gage should approach the edge of the end piece. This precaution will prevent the stress concentrations at the edges of the fixture from changing the gage stress distribution. The stress field around the gage is sufficiently complex without making it even more difficult to analyze.

Another requirement of a satisfactory test fixture is that the other end piece should not interfere with the zone of influence around the gage. This means that there should be a reasonable length of propellant between the end pieces, and that a specimen such as a "poker chip specimen" is not suitable for gage calibration.

The test fixtures may include special features such as the steel and Plexiglass ends of the fixture shown in Figure 3-10. The two gages at the steel end piece and the plastic end piece are subjected to somewhat different thermal loads under the same temperature excursions. The aim should be to simulate the eventual end-use condition, as when the gage is located in the grain, as closely as possible. If this condition is attained, the resulting calibration data should be satisfactory.

3.3.3 Gage Calibration Procedures in Elastic Media

If the material to which the gage is attached, or in which the gage is embedded, is linear and elastic, then calibration procedures follow well-established practice. The application of a step strain or stress (load) to the test fixture will result in a step change in gage output. The gage is calibrated by the application of several load or strain steps to the specimen

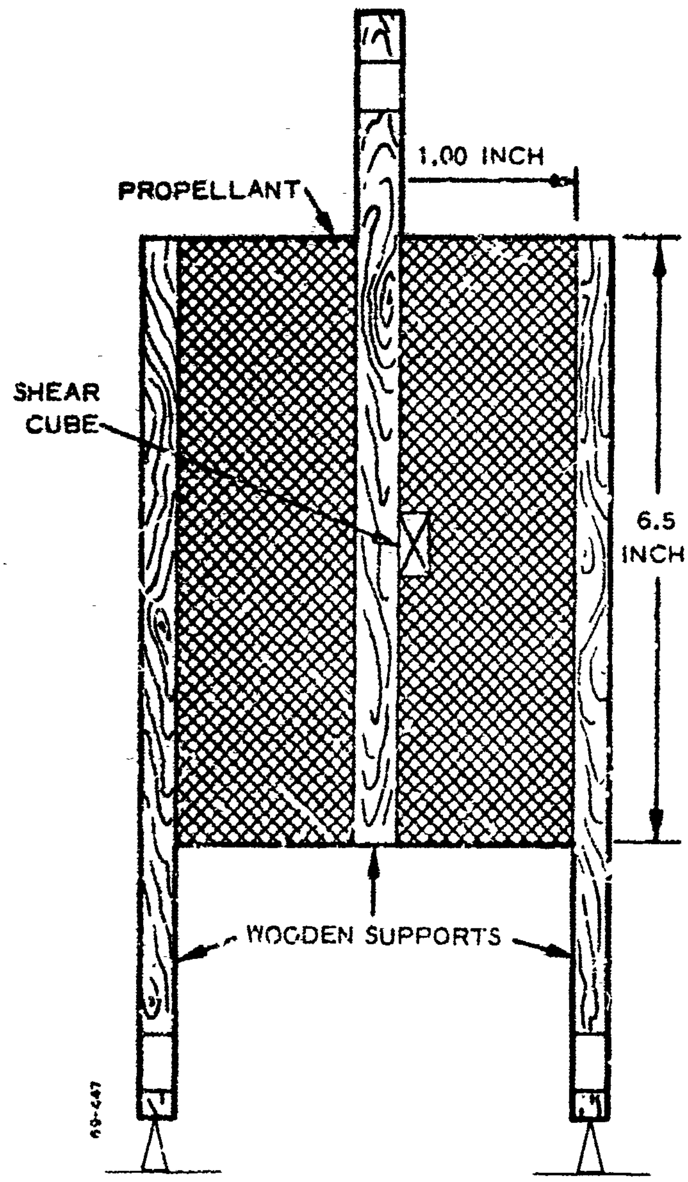


Figure 3-11 Shear Calibration Test Fixture

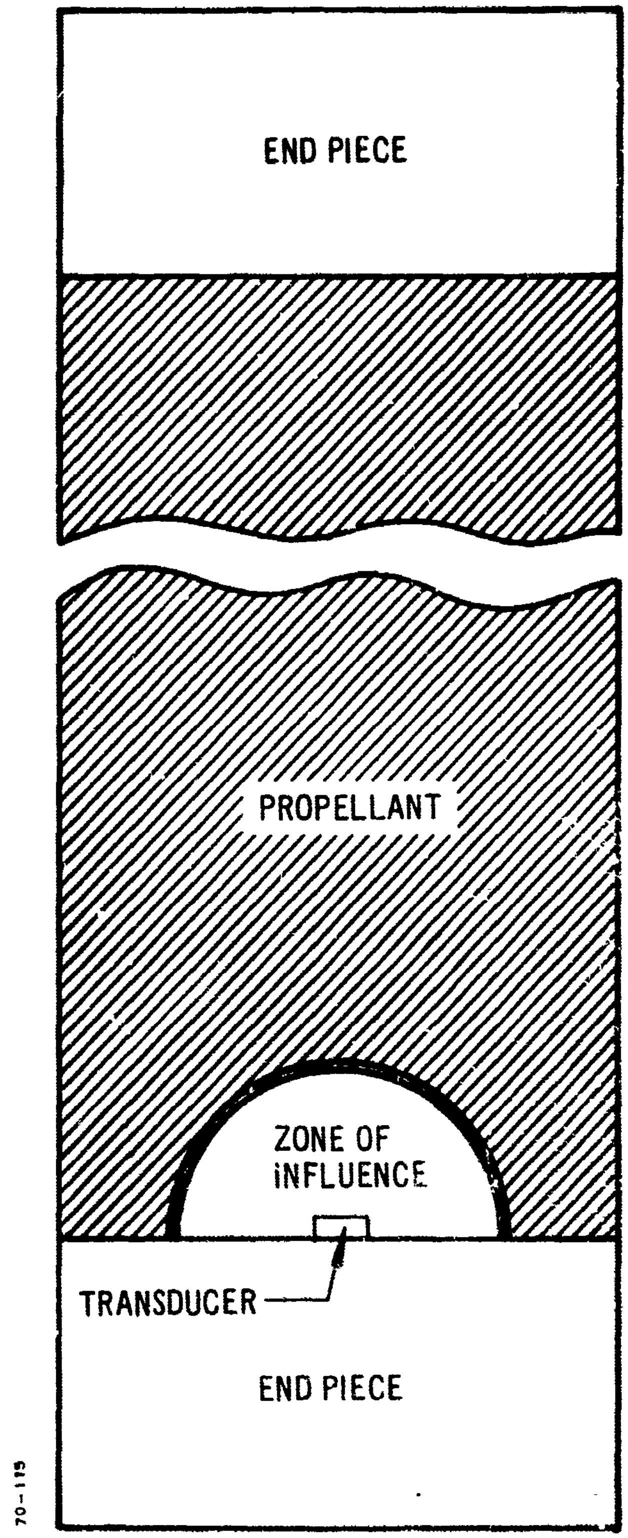


Figure 3-12 Schematic of Uniaxial Test Fixture Showing Zone of Influence of Gage at Propellant Interface

and the simultaneous noting of the corresponding gage readings. The gage output data are then plotted against load or strain and the best straight line is drawn through the data points. This procedure is illustrated in Figure 3-13, in which pressure calibration data from a 25-psi diaphragm gage embedded in propellant are given. The slope of the lines is the sensitivity of the gage at that particular temperature; typically, gage sensitivity decreases with temperature.

The gage sensitivity data may be plotted against temperature, as shown in Figure 3-14. If the material is simply elastic, then this curve is fixed and will not change with time, unless the properties of the propellant change.

In addition to the sensitivity data it is necessary to determine the zero load gage reading across the range of temperatures of interest. In most cases there will be an intrinsic shift in gage reading with temperature, which will have been determined and specified by the gage manufacturer. Curve A in Figure 3-15 shows a typical thermal zero shift signal for a well-compensated pressure gage. When the gage is embedded within propellant, the difference between the coefficients of thermal expansion of the gage and of the propellant produces a stress on the gage when no external load is applied to the system. Curve B of Figure 3-15 shows the thermal zero load gage output signal for the same pressure gage when embedded in a solid material under zero external load. There is a great difference between the pressure sensor data without the propellant and the data obtained with the gage embedded in the propellant. The important fact is the realization that Curve B will repeat itself during temperature changes and, therefore, this curve must be used as the zero stress reference for thermal stress measurements.

To illustrate this point, if the gage is embedded in the propellant at 120°F, a gage reading of approximately -2 mv will be obtained. The application of load (pressure) to the gage will result in output signal variations about the zero reading of -2 mv. Similarly, when the gage-propellant system is cooled to 40°F, a zero load output signal of -5 mv will be obtained. At even lower temperatures, e.g., -40°F, the zero load gage reading will be -45 mv, and any load applied to the system will result in signal variations about this value. The gage output values shown in Curve B of Figure 3-15 must be disregarded in measuring thermal stresses in a propellant grain; only the deviations from this curve are the result of externally applied stresses.

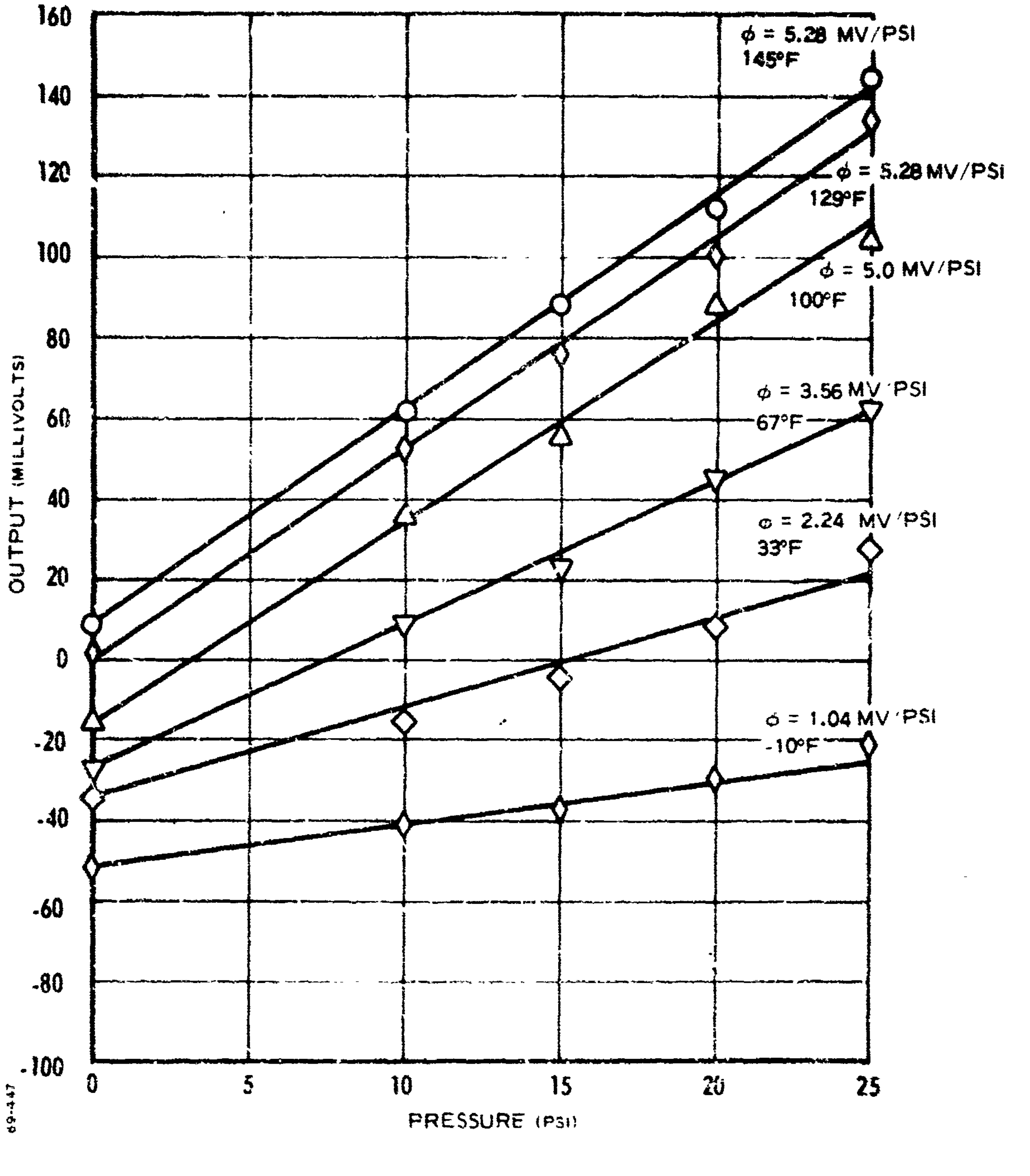


Figure 3-13 Gage Sensitivity Calibration Data for 25-psi Gage Embedded in an Elastic Material

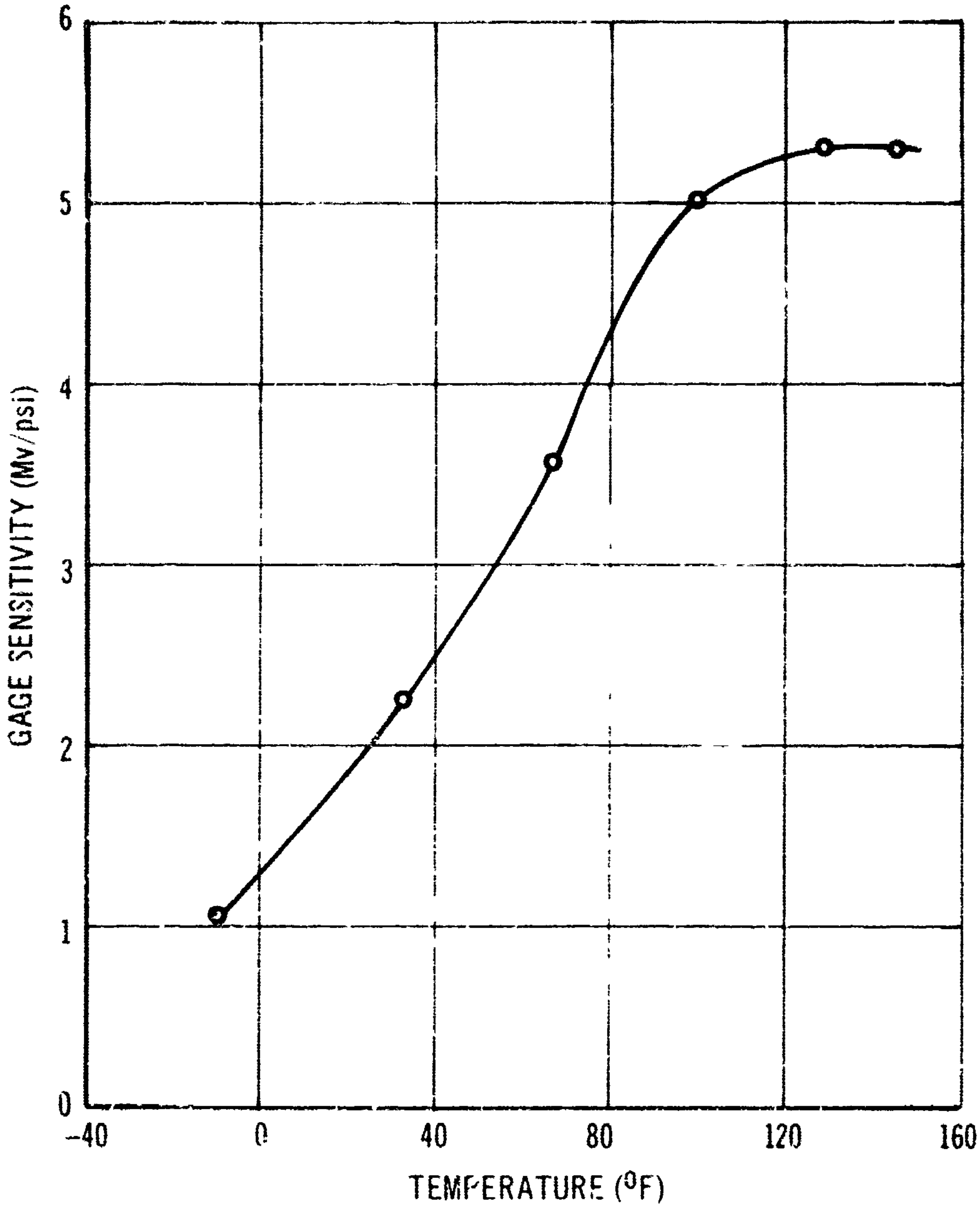


Figure 3-14 25-psi Transducer Sensitivity in Propellant versus Temperature

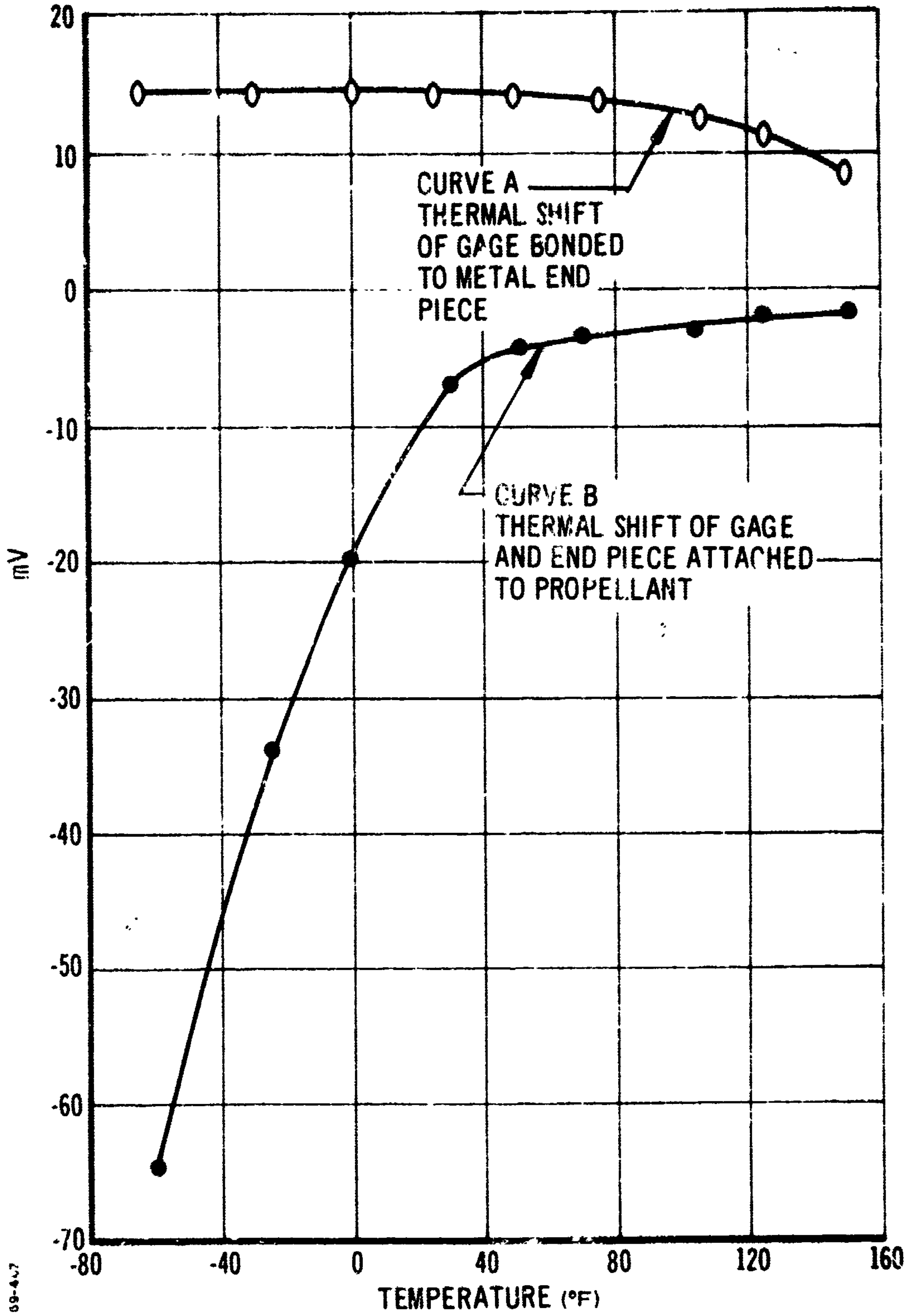


Figure 3-15 Zero Load Gage Readings for 25-psi Pressure Gage Before and After Bonding to Propellant

In summary, calibration of a gage embedded in an elastic material will consist of a determination of the thermal zero load gage response across the temperature range of interest, and the performance of step load isothermal tests to determine gage sensitivity, i.e., output signal divided by load. A sensitivity calibration test of the gage in the elastic material must be performed at several temperatures over the range of interest. Both the thermal zero load gage output data and the gage sensitivity data as a function of temperature will be required to interpret any subsequent gage output data.

In determining the load applied to the gage, it is necessary to use the analysis of the test fixture itself, without the gage, to ascertain the precise stress at the location of the gage caused by the externally applied load. For example, when the bond-in-tension specimen is used as a calibration fixture, the analytical curve shown in Figure A-5 (Appendix A) reveals that only 0.82 of each 1.0 psi applied axial stress is imposed at the gage location. This is not due to the gage; this reduction of stress at the center of the base plate is intrinsic to the test fixture and the material properties. Consequently, in the calibration of a gage in a bond-in-tension specimen, the applied axial load should be multiplied by the factor 0.82 to arrive at the load value that actually occurs at the gage location.

Professor Pister's analysis of the uniaxial test fixture containing a 150-psi gage gave the curves plotted in Figures A-6 and A-7, and revealed that the load factor at the gage location is not a constant but changes with the different types of applied load as well as with material properties. If a uniaxial load is applied to the specimen, then a factor of 0.9 should be applied to the applied stress to determine the stress at the gage location. However, if the gage calibration is conducted under a hydrostatic pressure loading condition, then there is essentially no attenuation of the applied stress at the gage location; i.e., the load factor is unity. Therefore, to arrive at an accurate calibration of a gage embedded in a text fixture it is essential to review the analytical results before performing the tests.

3.3.4 Stress Transducer Calibration Procedures in Viscoelastic Media

When a sensor is used in conjunction with an elastic material, the sensor output may be related directly either to the stress or to the strain in the material. Because the stress is uniquely related to the strain by

Hooke's Law, there is no ambiguity in the data. When the same sensor is used with a viscoelastic material, the stress is no longer a unique function of the applied strain, so that the sensor output has to be related by analysis or by experimental testing either to the stress or to the strain.

The methods of calibrating a transducer used with a viscoelastic material closely follow the techniques used for determining the viscoelastic material properties. Thus, constant load (creep) tests may be used to determine the material creep compliance, i. e.,

$$\frac{\epsilon(t)}{\sigma_o} = D_{crp}(t) \tag{3.1}$$

Similarly, if S(t) is the gage output signal under constant load conditions, a transfer function for gage sensitivity may be defined as follows:

$$\frac{S(t)}{\sigma_o} = \psi(t) = \text{gage sensitivity to stress (mv/psi)} \tag{3.2}$$

Observe, however, that another transfer function, the gage sensitivity to strain, also may be determined, e. g.,

$$\frac{S(t)}{\epsilon(t)} = Q(t) \tag{3.3}$$

By analogy with the stress relaxation, i. e., constant strain test, the strain sensitivity transfer function is probably best determined from relaxation test data as

$$\frac{S(t)}{\epsilon_o} = \beta(t) \tag{3.4}$$

In addition, there will be another function

$$\frac{S(t)}{\sigma(t)} = H(t) \tag{3.5}$$

which is the gage sensitivity in mv/psi as measured in the stress relaxation test.

Thus, in considering a calibration procedure with a viscoelastic material, the use of constant stress (creep) or constant strain tests enables four transfer functions to be determined analogous to the two material property functions: creep compliance and relaxation modulus.

There are only two independent gage transfer functions, $\psi(t) = \frac{S(t)}{\sigma_o}$ and $\beta(t) = \frac{S(t)}{\epsilon_o}$; the functions Q(t) and H(t) are related to $\psi(t)$ and $\beta(t)$ through the material property function $D_{crp}(t)$, the creep compliance, and $E_{rel}(t)$, the relaxation modulus. Thus Equation 3.3 then becomes

$$Q(t) = \frac{S(t)}{\epsilon(t)}$$

$$= \frac{S(t)}{\sigma_o} \times \frac{\sigma_o}{\epsilon(t)}$$

i.e.,
$$Q(t) = \frac{\psi(t)}{D_{crp}(t)} \tag{3.6}$$

Equation 3.5 then becomes

$$H(t) = \frac{S(t)}{\sigma(t)}$$

$$= \frac{S(t)}{\epsilon_o} \times \frac{\epsilon_o}{\sigma(t)}$$

$$H(t) = \frac{\beta(t)}{E_{rel}(t)} \tag{3.7}$$

Therefore, to the extent that $D_{crp}(t) \equiv 1/E_{rel}(t)$, the function $\psi(t)$ will be identical with H(t), i.e., $\psi(t) \simeq H(t)$ and $\beta(t)$ will resemble Q(t), i.e., $\beta(t) \simeq Q(t)$.

By performing creep and/or stress relaxation tests on the special test fixtures and monitoring transducer output as a function of time in addition to the stress or strain, the gage-propellant transfer functions may be obtained. The isothermal creep or relaxation modulus data are first shifted to obtain a master relaxation modulus or creep compliance-versus-reduced time curve. The isothermal transfer function data $\psi(t)$, Q(t), $\beta(t)$, and H(t) then may be shifted to produce master transfer function plots against reduced time.

As pointed out earlier, it is impossible to separate the viscoelastic gage calibration from the characterization of the viscoelastic material itself. It is necessary to make use of the time-temperature shift factors of the propellant material in order to properly reduce the gage sensitivity data. Consequently, it is often extremely useful to measure the material properties at the same time as the gage calibration is performed. The only additional requirement is that the deformation of the specimen be monitored during a constant load creep calibration test, or that the stress in the specimen be monitored during a stress relaxation or constant strain calibration test.

3.3.5 Alternating Tension and Compression Calibration Testing

The initial test procedures employed with the gage test fixtures closely resembled those used for the testing of propellant specimens. During the third year of the program, however, it was found that a more elaborate test procedure was necessary to make sure of obtaining accurate calibration data.

Data scatter obtained in a series of creep tests on the uniaxial test fixture led to an investigation of its causes. It appeared that the scatter was associated with the initial zero reading of the gage before a load was applied to the specimen. Because the area of concern is the change in gage signal caused by a change in stress, the gage signals measured during the loading phase are converted to output signal changes from the zero gage reading (prior to loading). Therefore, an error in the gage zero load reading will cause all of the gage signal change values to be incorrect and will produce errors in the gage sensitivity values.

The initial gage zero reading may be greatly influenced by handling during the test setup procedure, especially at the lower temperatures. For instance, if a test is begun and then stopped for some valid reason, the gage zero reading will have changed and, if a new test is begun within a short time interval, the measured signal changes will be incorrect. This is because a viscoelastic material has a "memory" of earlier events, and a gage embedded within a viscoelastic material "remembers" earlier loading histories.

The solution to this problem is to perform the calibration tests in a manner that will minimize the effects of earlier tests. Thus, the single-step tests performed as routine calibration procedures are inadequate, and multi-step loading tests are required. Further, to eliminate any progressive shift in the gage zero reading with time, it is recommended that alternating tensile and compressive loads be applied to the specimen, as shown in Figure 3-16. The anticipated gage readings from such a test sequence are also shown in this figure.

Figure 3-17 shows a sketch of the simple apparatus developed for applying alternating tensile and compressive loads to a uniaxial test specimen. The load application is controlled by means of the crosshead of the testing

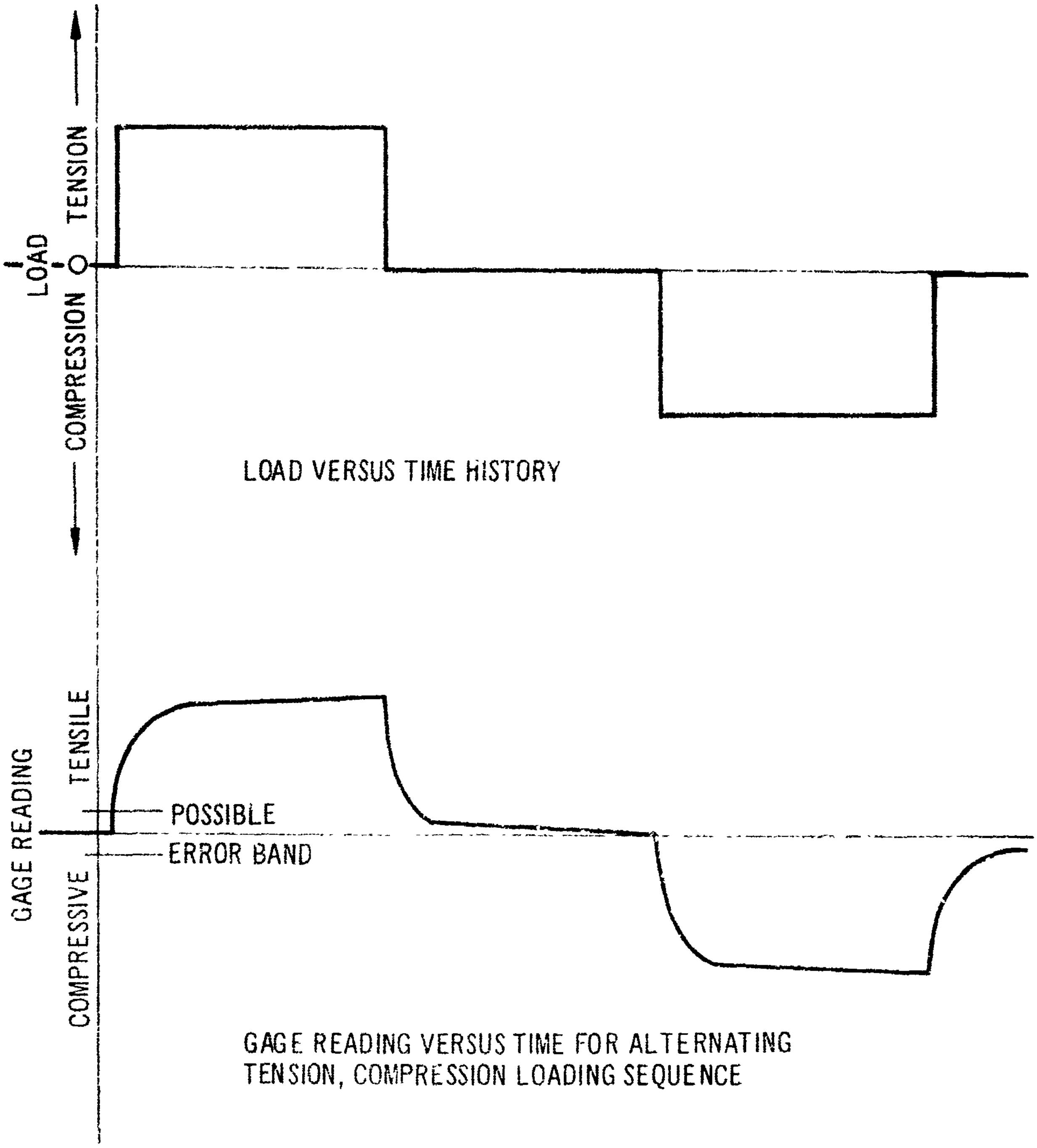


Figure 3-16 Alternating Tensile and Compressive Loading and Anticipated Gage Response

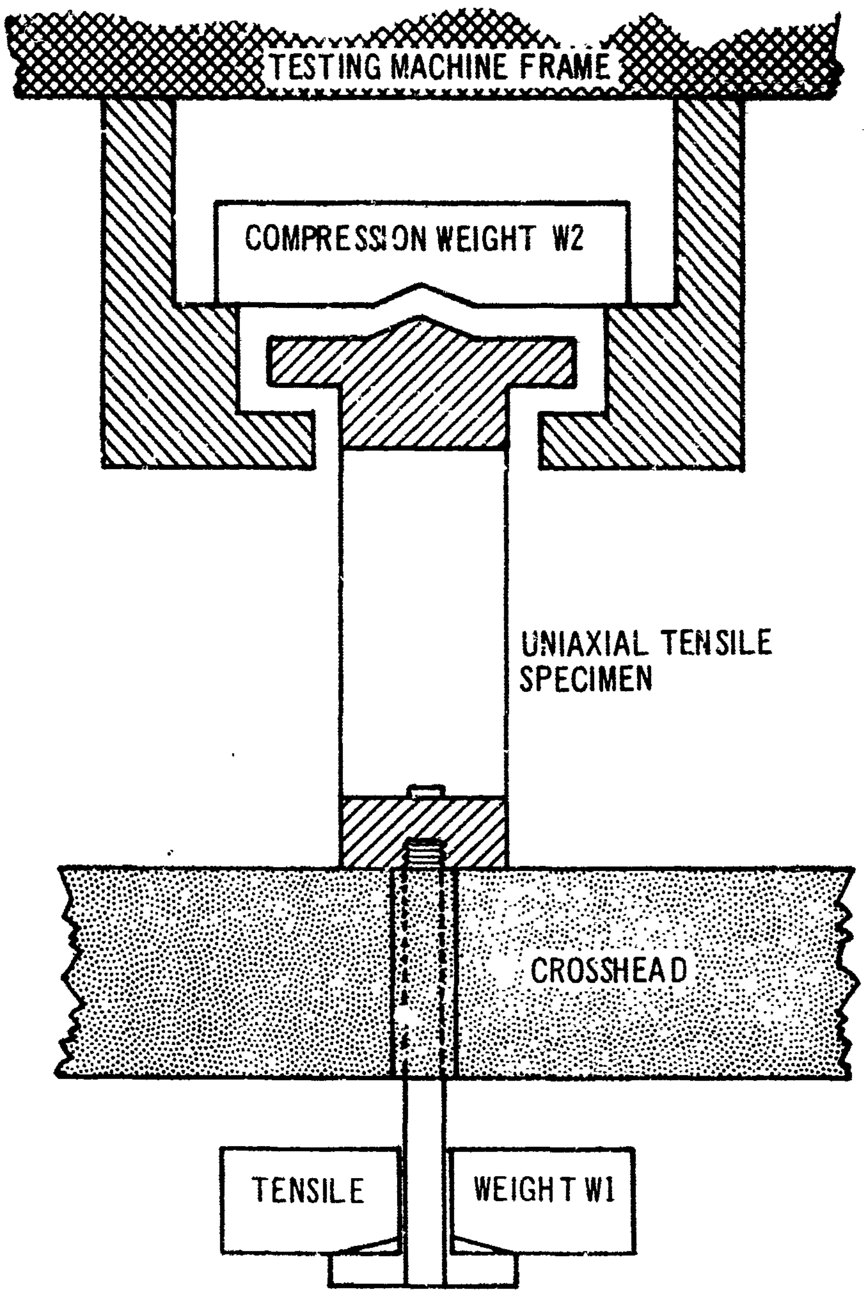


Figure 3-17 Apparatus for Applying Alternating Tensile and Compressive Loads to Uniaxial Test Fixture

machine; movement in an upward direction causes a compressive load (W_2) to be applied, whereas movement of the crosshead downward from the unloaded position causes the tensile load (W_1) to be applied.

A minor problem with this apparatus is the existence of two different zero load conditions. One is the tensile zero load condition and the other is the compressive zero load condition. These two zero load conditions are illustrated in Figure 3-18, where it will be noted the real zero load on a gage depends on its location in the test fixture. However, once this fact is appreciated, there is no further problem in dealing with the calibration data. Changing between the tensile zero load condition and the compressive zero load condition has to be treated like any other step change in load, with a sufficient time interval in between to allow approximate equilibrium to be attained.

Figure 3-19 shows typical data obtained from a series of tension and compression tests on the uniaxial inert propellant test specimen containing three 150-psi gages. The repeatability of the data is excellent and there is no doubt as to the proper location of either of the two zero load conditions.

3.3.6 Typical Calibration Data for a Stress Transducer in a Viscoelastic Material

A series of constant load creep tests was performed on a live propellant uniaxial test fixture containing a 25-psi diaphragm gage. The tests were performed at constant temperatures from 150 to -40°F.

As mentioned earlier in the section concerning strain transducer calibration, the best procedure is to translate the transducer sensitivity data (mv/psi, for a stress transducer) along the log time axis by the shift factors determined from the creep compliance test data. In many instances this will not result in a smooth gage transfer function, so that an additional vertical temperature correction factor, b_T, is required.

The 25-psi diaphragm stress transducer embedded in STV propellant produced the data shown in Figure 3-20, when treated as described above. The log a_T shift factors are plotted versus temperature in Figure 3-21 and the log b_T vertical shift factors are shown against temperature in Figure 3-22.

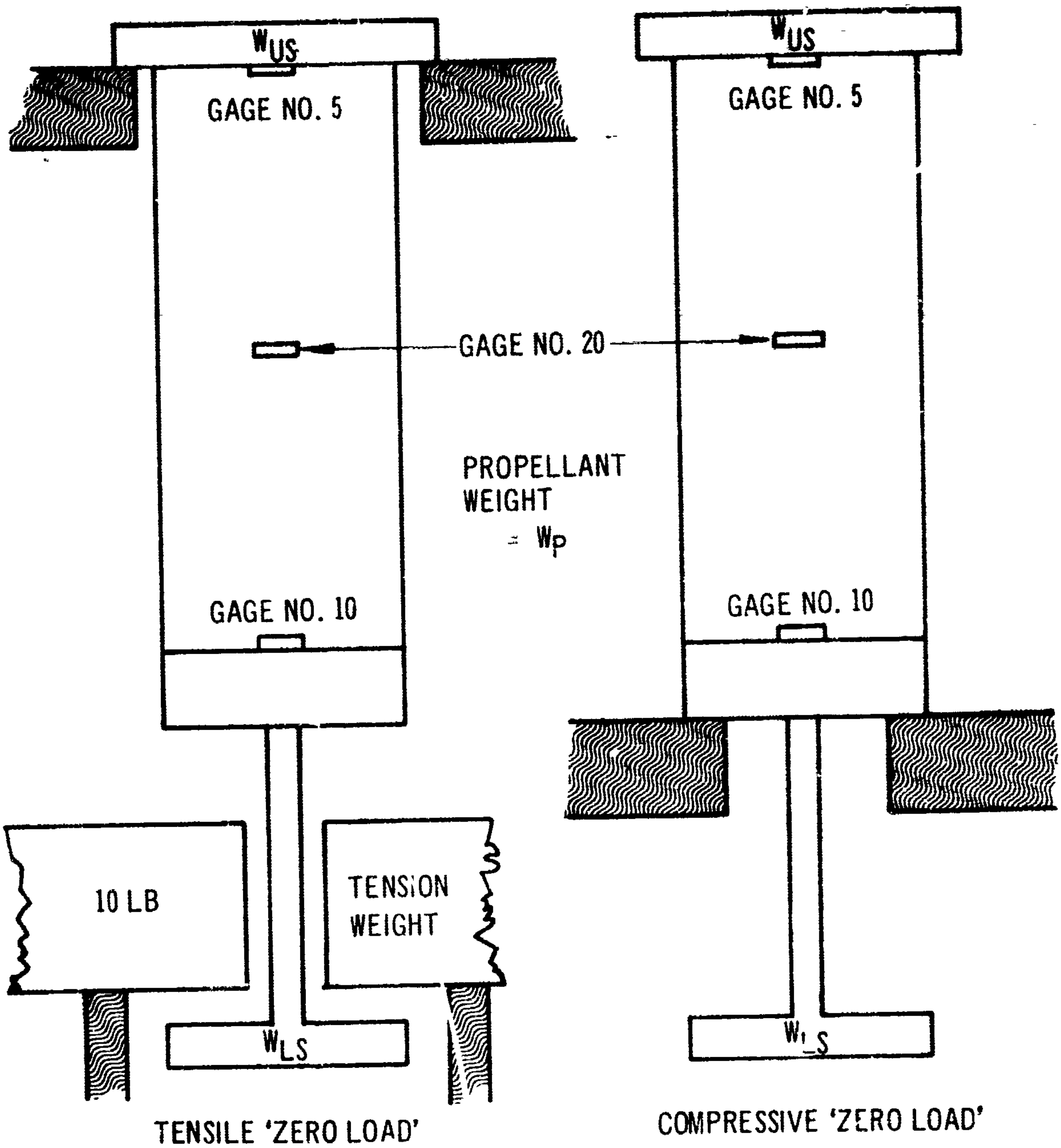


Figure 3-18 Tensile and Compressive Zero Load Conditions

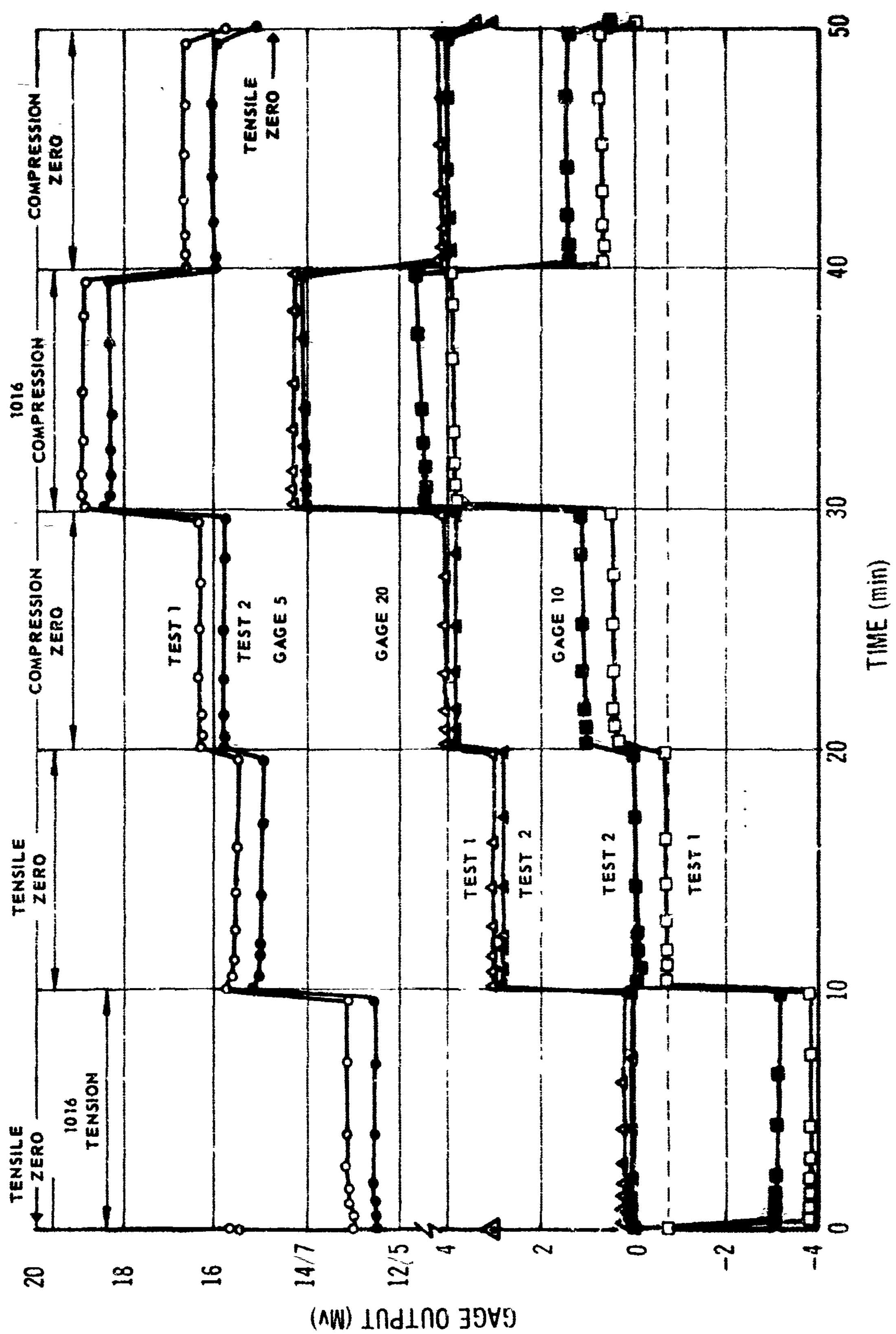


Figure 3-19 Uniaxial Test Fixture No. 2: Alternating Tension and Compression Test Data

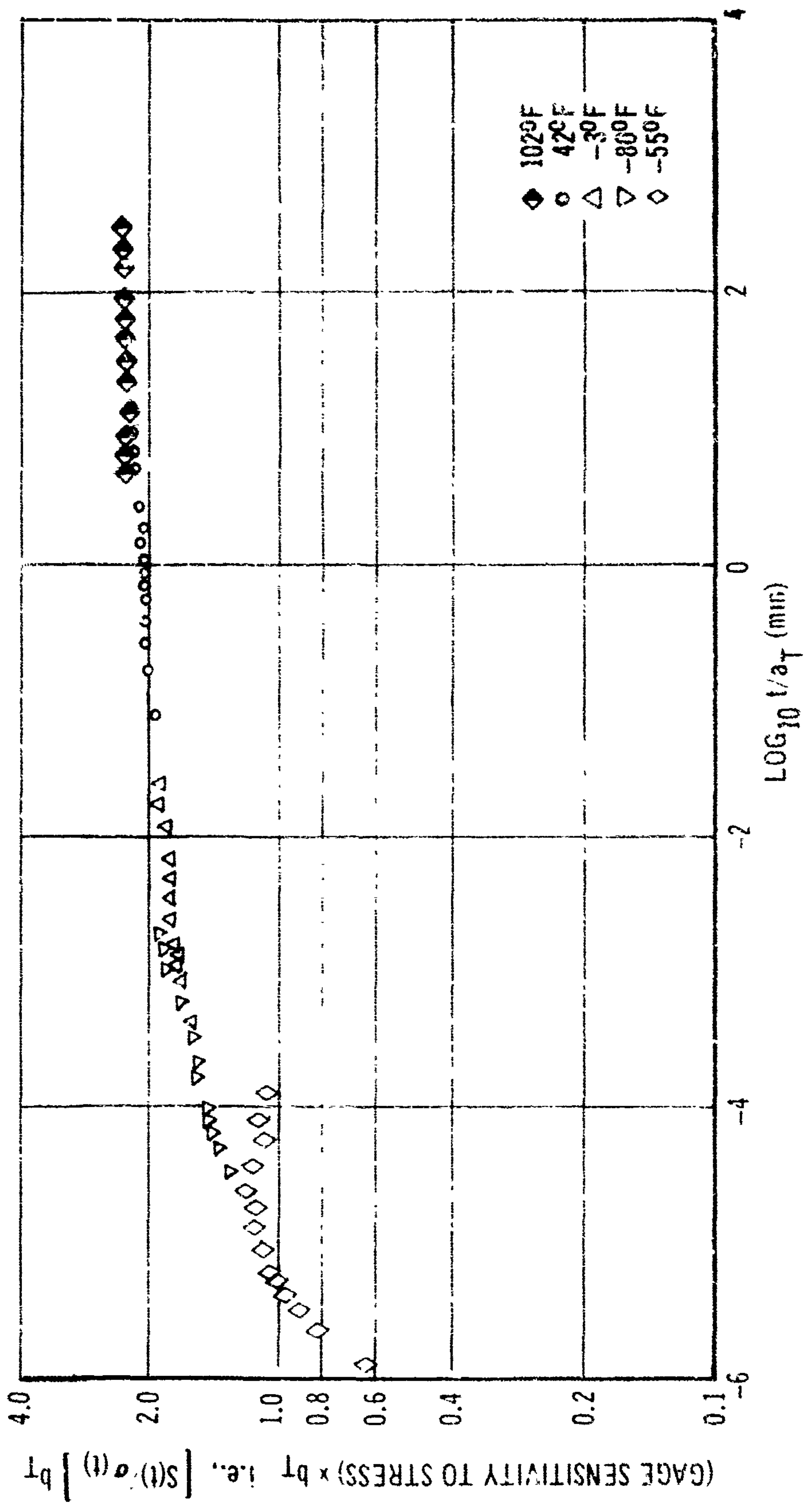


Figure 3-20 25-psi Diaphram Stress Transducer Calibration Data in STV Propellant

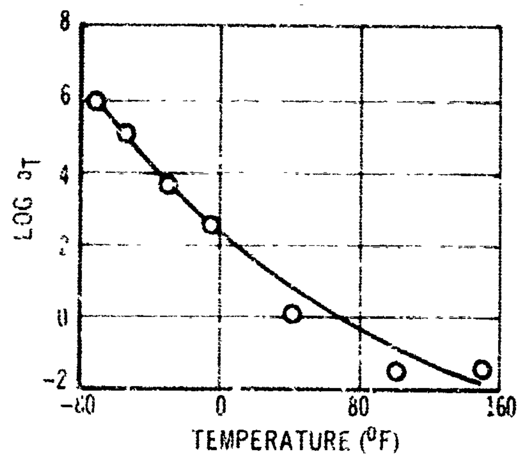


Figure 3-21 Time-Temperature Shift Factors Log a_T versus Temperature

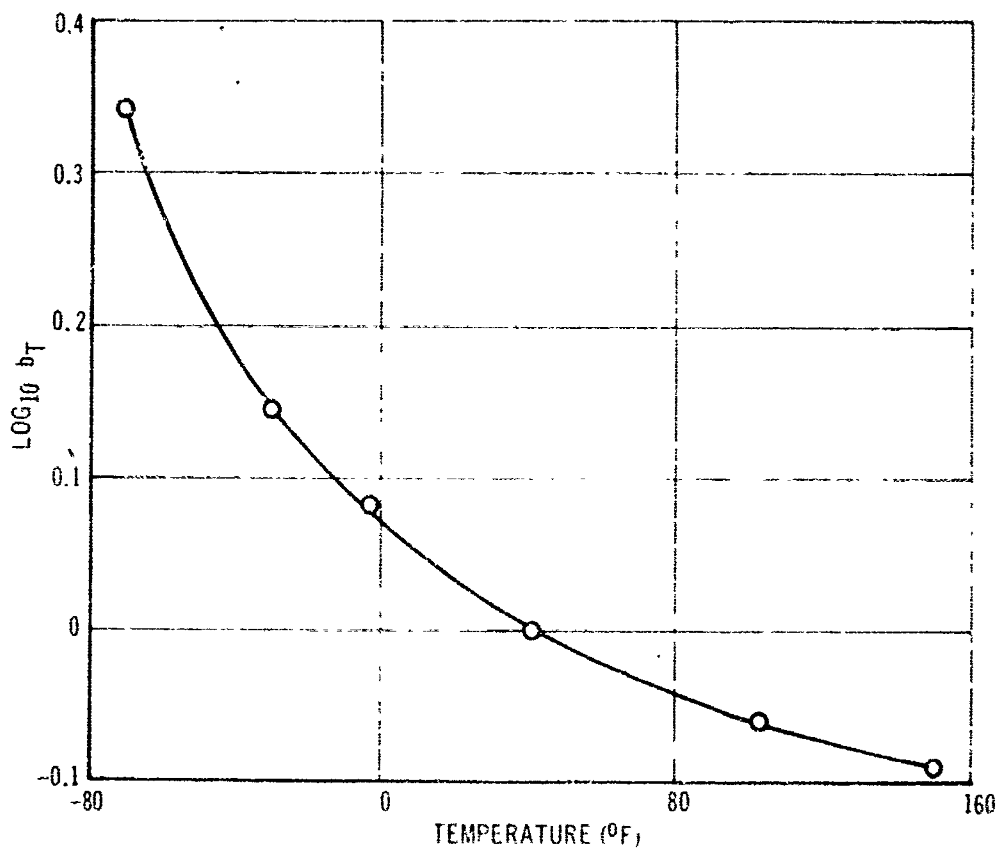


Figure 3-22 Vertical Shift Factors Log b_T versus Temperature

The vertical shift factors, log b_T, are required to account for those changes in gage sensitivity that are simply a function of temperature and are independent of the time-temperature relaxation effects of the propellant. They are essentially the same as the variation in gage sensitivity noted with some elastic materials as a function of temperature.

Embedded gages within viscoelastic media also exhibit changes in the zero load output signal as the temperature is changed. For this reason it is also necessary to perform a thermal calibration under zero load conditions across the temperature range of interest. In performing these tests, sufficient time should be allowed at each temperature for the gage to attain an equilibrium reading.

3.3.7 In Situ Calibration of Embedded Stress Transducers

The calibration tests considered so far have included a sensitivity and thermal zero error evaluation of the sensor itself across the desired temperature range, and a viscoelastic calibration of the sensor-propellant combination in a special test fixture. However, it is desirable to have a method of checking the performance of the transducer when embedded within the motor.

It is not feasible to evaluate each and every transducer in a special test fixture because of the high probability of damage in attempting to remove it from the test fixture. Therefore, the type or model of a specific transducer will be thoroughly evaluated in a special test fixture to ensure that it can perform satisfactorily. The stress transducers to be embedded within the motor require a thermal zero load calibration across the temperature range of interest and a pressure calibration at each of the various temperatures. These calibration procedures are required for the stress transducer bonded at its proper location in the motor and with a small piece of propellant cast over it. The propellant piece should be large enough so that the transducer "thinks" it is embedded within an infinite half-space of propellant; for a sensor having a diameter of ¼-inch, a piece of propellant with a radius of approximately 1.0 inch will be sufficient.

With the stress transducers mounted in their proper locations inside the motor case and with a piece of propellant cast and cured around them, they are then wired to the circuit board and power supply. The motor case and transducer assembly is placed in a temperature conditioning chamber and allowed to attain thermal equilibrium. Sufficient time must be allowed so that all transducer readings are constant. The thermal zero pressure readings are then noted and a step pressure is applied to the system and the transducer readings are again noted. With most normal propellants at high or moderate temperatures (down to 0^0F), there should be virtually no visco-elastic effects in the pressure readings. As soon as the pressure is stable at the set value, the gage should also be stable in its reading.

After the thermal zero error and step pressure calibration tests are completed, the motor may be disconnected. The interior of the case and the pieces of propellant surrounding the stress transducers should then be coated with liner material in readiness for casting of the grain.

Once the grain is cast, the various transducers will be giving a reading that depends on the stress exerted on the sensor. However, it is still possible to perform an in situ pressure step calibration of the stress transducers. The results of these tests should be very similar to those of the earlier step pressure calibration tests performed before the grain was cast. The thermal zero readings of the transducers will, of course, be changed and it will not be possible to confirm these zero stress data once the grain has been cast.

3.4 INSTALLATION OF STRESS TRANSDUCERS

3.4.1 Through-the-Case, Normal, and Shear Stress Transducers

In general, the through-the-case transducers must have a boss welded or, more commonly, bonded to the motor case. This boss is drilled through the center with a clearance hole for the gaged probe tip. The hole must also be drilled through the case. The probe tip should be contoured to produce a smooth and almost continuous surface with the inside of the motor case. This is not possible with through-the-case diaphragm transducers, all of which have a flat surface inside the motor case, to which will be bonded two semiconductor strain gage elements. The slight perturbation of the stress field caused by this discontinuity has not been found significant in operational tests.

Probably the most difficult single problem with the through-the-case piston type transducers is the prevention of adhesive from creeping up the small annulus between the piston and the motor case. Rocketdyne has developed elaborate methods for preventing this, including:

(1) Wrapping the piston with a coil of fine copper wire to prevent the intrusion of adhesive during the grain casting operation. The piston is held in place during the curing operation by a dummy transducer body. This dummy transducer is removed after the casting operation and the wire is carefully unwound from the probe tip. The real through-the-case sensor is then mounted in place on the motor case.

(2) A machined Teflon sleeve is used in place of the coil of wire. This plastic sleeve is then removed after the grain is cast and cured.

Once the transducers are in place on the motor case, they are unlikely to give further trouble. They also have the advantage of being readily removed after testing is completed, and they may be replaced by a dummy transducer in the event that the motor is to be fired.

Probably the only problem that may arise with the through-the-case shear stress transducers is ensuring that the boss is bonded properly in place, with the mounting holes for the transducer properly aligned relative to the motor axis. If this precaution is not observed, then it is unlikely that the arms of the shear sensor will align with the longitudinal axis of the motor. This will make reduction of the test data more complex than necessary.

3.4.2 Miniature Diaphragm Stress Transducers

Little is required in the way of preparation for the use of the miniature diaphragm stress transducers. They can be mounted directly on the motor case wall with an epoxy adhesive, or they can be bonded in place inside an insulated motor case with a liner material. These transducers are not very sensitive to mounting procedures, but they must be firmly attached in place.

The lead wires to internally mounted transducers present a problem in some instances. It has already been pointed out that taking the lead wires through the boot or flap at the end of a motor may occasionally prove to be a problem. This is especially true if it is necessary to fire the motor with the instrumentation in place. However, there are no rules-that may be laid down for solving this general problem; each has to be resolved on its own merits.

Care should be taken in installing internally mounted gages to make certain that the lead wires are properly identified. This is not as easy as it might seem. The use of paints, for instance, would be a good technique if the paints do not change color with temperature (during cure of the grain) or with age during subsequent long-term storage. Identification tags have a way of being lost at critical times during the program, requiring a long and tedious examination of the possible modes of connection. It is possible to lose all identification on the leads and still work out the correct method of wiring up the gage. However, it is not recommended that this be done regularly.

3.4.3 Embedded Shear Stress Transducers

Techniques for calibration of the shear stress transducers are essentially the same as those described for the shear strain transducers. The gages must be mounted in a shear test fixture and calibrated under constant load (or stress) conditions. After the constant load or stress tests have been completed at the various temperatures of interest, the gages must be carefully removed from the specimen and trimmed to fit snugly in the proper location in the motor case. The transducers may be mounted directly on the motor case wall or on the insulation, whichever is most suitable. It is suggested that the liner material should be used to bond the shear transducers in place, regardless of their location in the motor.

3.4.4 Transducer Installation in Existing Cast Motor

All of the techniques for mounting the stress or strain transducers considered so far have been based on the assumption that the gages could be installed before casting. However, in some instances, it may be necessary to install gages in an already cast and cured motor. This problem was faced in the Instrumented First Stage Minuteman Motor program, which was conducted by AFRPL at Thiokol and Rocketdyne.

The solution to the problem of mounting transducers after casting was to chemically etch 4.0-inch-diameter holes through the case wall in the locations where the stress transducers were to be placed. Holes were then drilled in the propellant grain (to a depth of 3.0 inches in the Minuteman motor).

Plugs were then prepared, consisting of a cylinder of the Minuteman propellant with a piece of metal case attached at one end. By chemically milling small holes in this piece of case wall, it was possible to mount through-the-case normal and shear stress measuring gages on the case metal with the sensitive element, either the piston probe tip or the diaphragm, in contact with the propellant of the cylinder.

Thermal and step pressure and load calibration tests were then performed on the 4-inch-diameter cylinders of propellant containing the normal and shear stress measuring transducers. This technique resembles that used for calibrating the internally mounted diaphragm gages by casting pieces of propellant around them when they are located inside the motor case.

When calibration was completed, the plugs of propellant containing the transducers were carefully trimmed for a snug fit in the corresponding hole in the Minuteman Motor. The motor was heated to cure temperature before this trimming operation because the size of the hole and of the plug changed with temperature. The plugs were then bonded into the motor with a liner material. A doubler plate of the motor case material was bonded to the outside of the motor case with an epoxy adhesive.

A sketch of a typical "hole assembly" is given in Figure 2-23.

The procedure outlined above may seem tedious and lengthy, but all of the steps taken were necessary to ensure good data from the Minuteman motor tests. The quality of the resulting data more than compensates for the trouble taken beforehand.

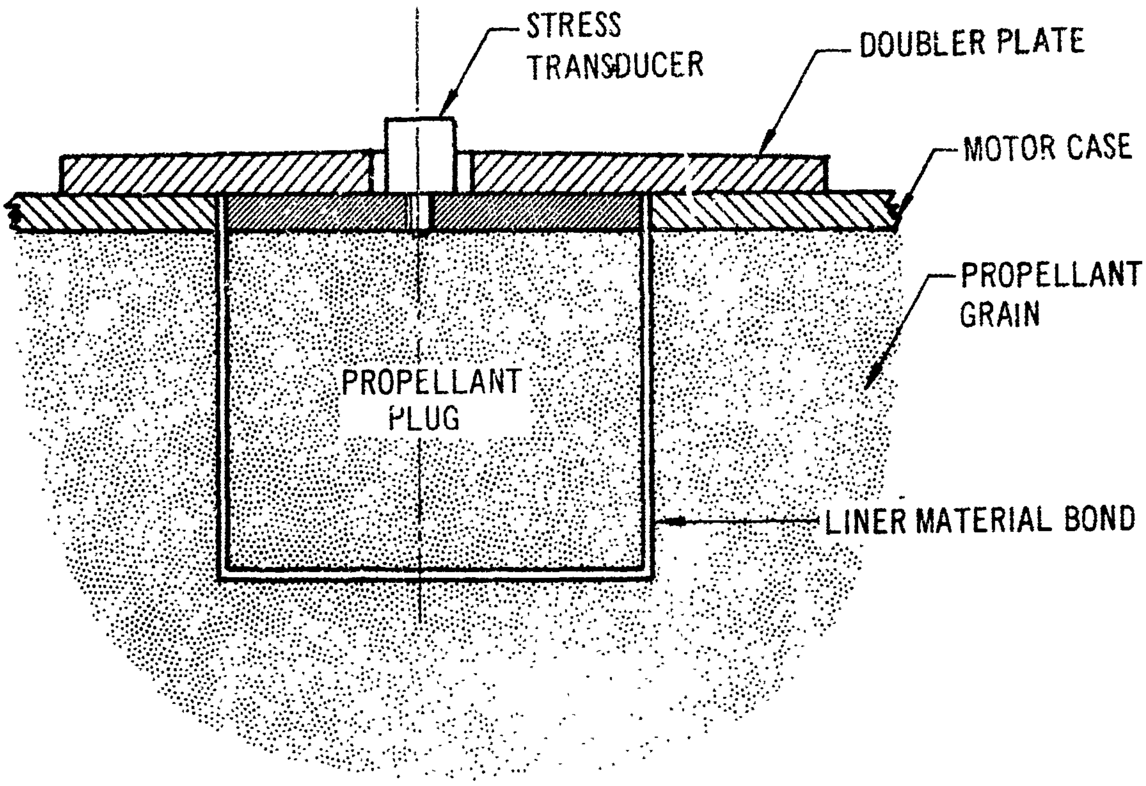


Figure 3-23 Sketch of Typical "Hole Assembly" for Minuteman First Stage Motor

Section 4
TEMPERATURE MEASUREMENT

4.1 TYPES OF TEMPERATURE SENSOR

Two types of temperature sensor may be used in conjunction with a solid propellant rocket motor:

- Thermocouples
- Thermistors

The following subsections deal briefly with the essential features of these devices and the manner in which they may be positioned in the propellant grain.

4.1.1 Thermocouples

A thermocouple consists of a pair of dissimilar wires, e.g., copper and constantan, which are formed into two junctions. One junction is the "reference" junction and the other is the active temperature measuring sensor. When the two junctions are maintained at different temperatures, a current flows in the circuit and an EMF is generated between the active and reference junctions. The device is, therefore, an active or self-generating type of sensor.

Different wire combinations may be used for different temperature ranges, but the copper-constantan thermocouple is the one most generally used for laboratory tests. Thermocouples are routinely used in laboratories for temperature measurement and special millivolt meters are available calibrated directly in degrees of temperature.

Many test programs have made use of thermocouples cast into propellant grains to measure temperature gradients in the web during environmental exposure. Thermocouples were used exclusively in the STV program for the measurement of grain and case temperatures.

There are three possible problem areas in connection with the use of thermocouples for grain temperature measurements, especially for measuring in-flight grain temperatures. These are as follows:

(1) Thermocouples are comparatively insensitive devices producing a small signal, ~8 mv, for a temperature range between 250 and -100°F. Therefore the recording devices must contain amplifiers

to give a reasonable signal level. The small signal level may also result in a poor signal-to-noise ratio in the data.

(2) The wires joining the measuring junction to the reference junction must consist of identical material throughout their length, i.e., copper wires cannot be used to connect the constantan wire to a recorder. A pair of wires, e.g., copper and constantan, must be used throughout the length of the thermocouple. In many instances, such as routing wires through pressure-tight bulkheads or end closures, it is often inconvenient to have to provide special constantan pins for thermocouple lead wires.

(3) The recorder must contain a reference junction either held at a fixed temperature or provided with a temperature-compensating system if accurate temperatures are to be measured with a thermocouple.

Because of these possible problem areas, the alternative temperature measuring sensors, i.e., thermistors, must be considered.

4.1.2 Thermistors

A thermistor is a temperature-dependent semiconductor resistor that acts as a passive, or nonself-generating, sensor. Thermistors must therefore be energized with a current supply to provide an output signal. Probably the best arrangement for accurate temperature measurement in a propellant grain is the bridge circuit shown in Figure 4-1. With this circuit, it is possible to zero the bridge output at a specified temperature and to calibrate the output signal as a function of the thermistor temperature. Thermistors usually are much more sensitive than thermocouples but have a more restricted range of temperatures, within which they produce a reasonably linear output-temperature relation.

However, there are commercially available thermistors that will operate well over the required temperature range, i.e., 165 to -65°F. A stabilized DC power supply is required for the thermistors, but in general this will not be a problem because the same power supply used for the other resistance strain gage devices may be used for the thermistor bridge circuits. Also, any recording system employed for the stress or strain sensors

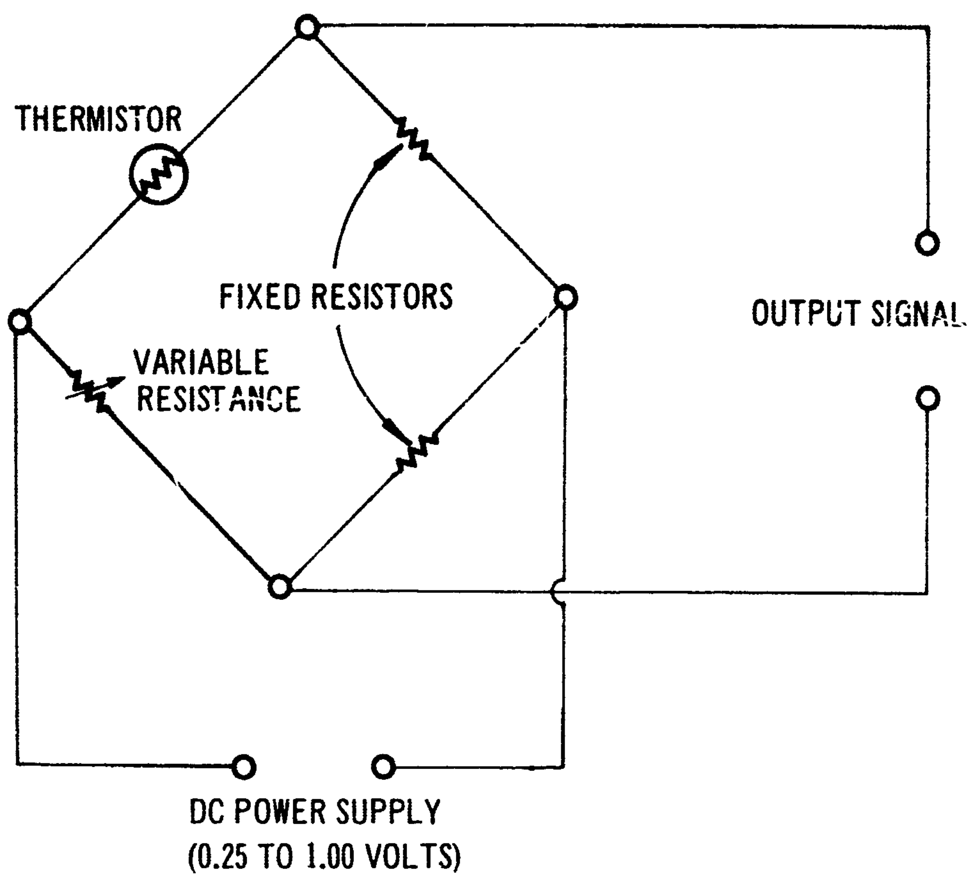


Figure 4-1 Thermistor Bridge Circuit

will work equally well with the thermistors. Furthermore, copper wires may be used to connect the thermistors to the bridge circuit and to the recorder.

Thermistors were used for measuring the grain temperatures in the Flight Test Bomb Dummy Unit. Special devices consisting of a thin layer of semiconductor material bonded to a 0.001-inch-thick substrate of nickel were used in the BDU. These devices are manufactured by VECO (Victory Engineering Co.) under the trade name of "Thinnistors". They have an extremely rapid response to temperature and, if properly oriented, will give an indication of the temperature at a precise location. Also, because of their large surface area, the thermal contact between the sensor and the propellant is very good.

4.2 INSTALLATION TECHNIQUES

Temperature sensors can be installed within a propellant grain in several ways. In the case of the STVs, the sensors were bonded in place in small pieces of cured propellant so that their exact locations could be predetermined. The cured propellant pieces then were bonded to the STV case and coated with liner material. The propellant grain finally was cast around it. This technique gave excellent results and X-ray photographs after cure did not reveal voids or unbonds between the thermocouple propellant blocks and the remainder of the grain.

If this technique is not possible for any reason, a simple alternate approach is to locate a small lead shot on the end of the thermocouple and merely to insert it in the grain immediately after casting and before cure. The precise position of the temperature sensor then may be determined from X-ray photographs. The small lead shot is clearly visible in the X-ray.

Section 5
TRANSDUCER DATA INTERPRETATION

5.1 INTRODUCTION

The simplest form of data reduction for a transducer consists of determining a constant, Δ_o, which, when multiplied by the gage output signal (in millivolts), gives the value of the stress or the strain.

Thus $\sigma = \Delta_o \times S$ (5.1)

where S = Signal from transducer
Δ_o = Calibration constant

In practice, most transducers are rarely as uncomplicated as this. In many cases the calibration constant Δ_o will be temperature-dependent so that different values must be used for tests conducted at different temperatures.

Similarly, in some cases, the calibration will not be constant with time, i.e., the value of Δ_o will be time-dependent.

In the general case, therefore, the interpretation of a transducer's output data can be a complex integration problem requiring knowledge of the time and temperature history of the system.

A general equation for solving transducer data reduction problems is presented in the next subsection, and the simplifications obtained for various simple types of time and temperature history are discussed.

5.2 INTEGRAL EQUATIONS FOR DATA REDUCTION

5.2.1 General Case of Transducer in Viscoelastic Medium

It was shown in earlier sections of this report that in the most complex case, the calibration data for a stress or strain sensor embedded in a viscoelastic medium required a translation along the log time axis to account for variation in temperature. In addition, it was shown that a vertical translation along the gage sensitivity scale was required, to account for inherent variations in transducer sensitivity with temperature.

For the case of a generalized complex environmental history involving temperature and time changes, the gage output S(t) may be interpreted as a time-varying stress $\sigma(t)$ or a time-varying strain $\epsilon(t)$, by means of the integral equations

$$\sigma(t) = \int_0^t \left[1/b_T\right] \phi(t' - \tau') \frac{d}{d\tau} \left[S(\tau)\right] d\tau \tag{5.2}$$

and

$$\epsilon(t) = \int_0^t \left[1/b_T\right] \theta(t' - \tau') \frac{d}{d\tau} \left[S(\tau)\right] d\tau \tag{5.3}$$

where

b_T = Vertical shift factor applied to gage calibration data

$\phi(t')$ = Inverse transducer sensitivity to stress versus reduced time

$\theta(t')$ = Inverse transducer sensitivity to strain versus reduced time

$S(t)$ = Transducer output signal as function of time

These integral equations must be solved by numerical techniques, and the programs devised for determining the stress/strain from stress relaxation data are particularly well suited to this type of calculation. An example of the use of this type of program for the interpretation of transducer output data is given in Reference 2.

5.2.2 Transducer in Elastic Media

If the embedding material is elastic and not time-dependent, then Equations 5.2 and 5.3 can be simplified as follows:

The time-dependent functions $\phi(t' - \tau')$ and $\theta(t' - \tau')$ are replaced by constants ϕ_o and θ_o, respectively. Equation 5.2 then becomes

$$\sigma[T] = \int_{T_o}^{T} \left[1/b_T\right] \phi_o \frac{d}{dT} \left[S(T)\right] dT \tag{5.4}$$

and Equation 5.3 becomes

$$\epsilon[T] = \int_{T_o}^{T} \left[1/b_T\right] \theta_o \frac{d}{dT} \left[S(T)\right] dT \tag{5.5}$$

It is more usual to write the term $\left[1/b_T\right]\phi_o$ as a single term, $\Delta(T)$, implying that the transducer response is a constant at a constant temperature, but changes with temperature. With this simplification, Equation 5.4 becomes

$$\sigma[T] = \int_{T_o}^{T} \Delta(T) \frac{d}{dT}\left[S(T)\right] dT \tag{5.6}$$

Furthermore, for the case of a constant temperature, the equations reduce to the simple expression given earlier, i.e.,

$$\sigma = \Delta_o \int_0^S dS = \Delta_o S \quad \text{(Ref Eq 5.1)}$$

Section 6
LIST OF REFERENCES

(1) Leeming, H., et al, Final Report, Solid Propellant Structural Test Vehicle, Cumulative Damage and Systems Analysis, Technical Report No. AFRPL-TR-68-130, Lockheed Propulsion Company, October 1968

(2) Leeming, H., et al, Final Report, Solid Propellant Structural Test Vehicle and Systems Analysis, Technical Report No. AFRPL-TR-70-10, Section (2), Lockheed Propulsion Company, March 1970

(3) Burton, J.D. and Noel, J.S., Stress State Transducer Development Program, Final Report No. AFRPL-TR-70-102, Rocketdyne, Solid Rocket Division, October 1970

(4) Jones, W.B., et al, "Surface and In-Situ Physical Properties and Instrumentation for Ballistic Missile Motor Grains," 1971 JANNAF Combined Propulsion Meeting, November 1971

(5) De Hart, R.C., et al, "Techniques for Acquiring Subsurface Displacements in Viscoelastic Material," Bulletin of Fourth Meeting ICRPG Working Group on Mechanical Behavior, CPIA Pub. No. 940, November 1965

(6) Schwartz, D.S., Development of Unidirectional D.C. Axial and Radial Flexible Propellant Shear Strain Transducers, Gulton Industries, Inc., Final Report to Hercules Powder Co., November 1963

(7) Hibex Solid Propellant Transducers, The Boeing Company, Report No. D2-99589-1, Contract No. DA-01-021-AMC-10696(Z), (C)

(8) Sciammarella, C.A. and Durelli, A.J., "Moiré Fringe as a Means of Analyzing Strains," Proc. ASCE, 87 EMI, February 1961

(9) Hart, W.D., "Moiré Method for the Measurement of Strains in Solid Propellants," CPIA Bulletin No. 3, Working Group on Mechanical Behavior, NASA N65-13607, October 1964

(10) Morse, S., et al, "Geometry of Moiré Fringes in Strain Analysis," Proc. ASCE, 86 (No. EM4), August 1960

(11) Vinckier, A. and Dechaena, R., "Use of the Moiré Effect to Measure Plastic Strains," ASME Trans. 82. D, June 1960

(12) Durelli, A. J. and Daniel, I. M., "Structural Model Analysis by Means of Moiré Fringes," Proc. ASCE, 86 (No. ST 12), December 1960

(13) Chelner, H., <u>Some Recent Developments in the Semiconductor Transducer Field</u>, a Rocketdyne Report

Appendix A
GAGE-GRAIN INTERACTION

A.1 INTRODUCTION

"The most important principle in measurement engineering is that a valid measurement is made when the maximum amount of information is transferred with a minimum amount of energy. The moment energy is withdrawn from the process to be observed, the process itself is altered." This quotation from Stein (Ref A-1) aptly summarizes the problems of measurement within a viscoelastic propellant grain. In this context, the precise variable being measured is immaterial; a valid measurement can be obtained only if minimum energy is withdrawn from the system, i. e., the propellant grain.

Stress, strain, displacement, and temperature characteristics of a solid propellant rocket motor are point functions of space and time. Accordingly, any attempt to embed a measuring device in the interior or on the surface of a motor creates problems from at least the following standpoints:

- The finite size of a measuring device rules out the possibility of obtaining information at its location point. Rather, some kind of "average in a neighborhood" is recorded. If the spatial gradients of the fields measured are not too severe, this limitation may not be serious.
- In virtually all instances the embedded device has mechanical and thermal properties different from the propellant, producing nonhomogeneity in the propellant. This leads to perturbations (interference) of the free field that would not have existed in the absence of the measuring gage.
- The presence of the propellant medium surrounding the device has the effect of modifying its response. The extent of the response change is a measure of the difficulty of the gage-grain interaction problem.

Because the interference or interaction between the gage and the propellant cannot be eliminated, its influence must be determined quantitatively to use the gage properly. If the purpose of a measuring gage is to indicate the value of the field quantities at a particular point over a certain range of time, it is clear that a proper calibration of the gage is required. [Calibration, in this context, involves considerably more than testing a gage placed in a fixture to relate "input" to "output", as discussed in Appendix B.]

To aid in understanding how the techniques by which energy withdrawal from the system is minimized, a brief description of the various types of transducer is presented below.

A.2 TRANSDUCER CLASSIFICATION

The term transducer is taken to mean a device which converts energy from one type to another. In this report we are more concerned with the more restricted group of devices which Neubert (Ref A-2) has called "Instrument Transducers". He uses this term to define devices that convert energy (transduce) for the specific purpose of measurement. In this context, the term transducer is almost identical in meaning with the term "gage", i.e., a measuring instrument. The terms are used interchangeably in this report because of the common use of the term "strain gage" in which gage is misused in place of transducer.

Transducers (i.e., energy conversion devices) may be broadly classified as either self-generating or non-self-generating devices. The differences between these two types may be summarized as follows:

- Self-generating devices produce an energy output with a single energy input. For example, piezoelectric crystals, thermocouples, bilinear thermal expansion devices, etc.
- Non-self-generating devices require two energy inputs to produce an energy output. This class includes all passive (impedence based) elements such as resistance thermometers, resistance strain gages, capacitive displacement sensors, photoelasticity, Moiré fringe methods, etc. These devices require both a primary energy input from the quantity being observed as well as an auxiliary excitation, or biasing input, needed to transmit the information from the primary input to the transducer output.

For example, the resistance change in a strain gage induced by the primary input (strain) must be carried by a biasing electrical voltage and current input to the gage.

The biasing input, when electrical in nature, may be DC, AC, or a pulse train. The actual information-carrying property may be amplitude, amplitude modulation, frequency or phase (modulation) pulse code, etc.

Value may be sensed by direct observation of the transducer output energy (in general a variation of the biasing input quantity) as is done in most dynamic or transient observations of primary input. Alternatively, the information content may be sensed by nulling the output energy through variations in the biasing input energy and observing the necessary changes in the biasing input parameters, such as an arm of a Wheatstone bridge. The more accurate method is generally a null method.

The primary and biasing energy input as well as the output may take any one, or combination of two or more, of the following forms: mechanical, electrical, optical, chemical, thermal, magnetic, acoustic, and nuclear.

A.3 TRANSDUCER REQUIREMENTS

An ideal measuring device would measure that which is required without modifying the system being measured. Few devices approach this ideal. Therefore the problem becomes one of determining in what manner the measuring sensor's presence influences the system, and from this, determining the correct magnitude of the response as if the instrument were not present.

With regard to real systems, attempts are being made to measure stress, strain, and temperature at the boundaries and the interior of rocket motor grains while being subjected to environmental and field loads. The overall problem may be simplified by reviewing the separate requirements of deformation measurements at a free surface, deformation and stress measurements at a constrained surface, and measurement of stress, strain and temperature within the interior of the propellant grain.

A.3.1 Free Surface Deformation Measurements

A wealth of experience is available in the area of free surface deformation measurement, and many techniques have been developed for this purpose. The ideal device is one that imposes no restraint on the surface deformation, i. e., a zero stiffness gage. Many potential devices, such as the Moiré fringe method of surface strain measurement, closely approach the ideal.

The use of resistance strain gages bonded to metal surfaces approaches the ideal in that the effects of the transducer are usually negligible, but only on relatively rigid surfaces such as metals.

The principal requirement of an ideal free surface deformation measuring device is that it should have infinite compliance (zero stiffness), thereby imposing no loads on the surface and withdrawing no energy from the body being measured.

A.3.2 Measurement at Constrained Surfaces (Interfaces)

This problem is more complex than that of free surface deformation measurement because both stresses and strains are present at the interface. Measurement difficulties are greatly reduced when either of the following two conditions are approached:

- The motor case wall is so thin that the strains measured on the outer surface are identical to those at the inner surface, and the strains are large enough to be accurately measured; energy transfer is negligible because compliance of the gage is extremely large compared to compliance of case.
- The motor case wall is so thick that strains are negligible and the case may be regarded as rigid; again, no energy transfer occurs because deformation of the gage approaches zero.

In most solid propellant motors, one or the other of the conditions can be met so that the problem then reduces to one of determining the stresses or strains at the interface. Because of the compliance mismatch between the case and the propellant, measurements can be made with reasonable accuracy at this boundary.

In contrast to a deformation measuring device that must deform yet impose no restraint on the deformation, a stress measuring sensor must measure the applied force (stress over the area of the sensor) but must not deform under the load. An ideal stress sensor must possess zero compliance (or infinite stiffness).

To illustrate this point, consider the electronic analogy of measuring voltage or potential differences across a simple DC network. Connecting a voltmeter across the circuit will always produce a meter reading, but the closeness of that meter reading to the correct value depends on the internal resistance of the meter and the impedence of the network. The problem is that an electrical measuring device requires current to operate, and consequently withdraws energy from the system. The meter will draw very little current and an accurate voltage reading will be obtained providing the internal impedence of the meter is much greater than that of the network.

If we relate voltage to stress, and current to strain, we have the mechanical analogy; i.e., the stress measurement problem. The electrical analog shows that to measure stress (voltage) as accurately as possible, the measuring instrument (stress gage) must deform as little as possible during measurement; i.e., the stress gage must have as high a mechanical impedence (stiffness) as possible.

A.3.3 Measurement of Stress and Strain Inside a Grain

The device embedded within a grain to measure stress or strain must not significantly disturb the stress-strain field. Preferably, there should be no change in the field through the introduction of the gage. This may be achieved by using only a device with the same properties as the propellant. There are materials which approach this ideal that may be used as transducers, e.g., conductive rubbers or plastics that exhibit changes in electrical properties when subjected to deformation. It is feasible to conside their use in a propellant grain. Materials of this kind are sensitive to deformation and may be used as strain sensors. Unfortunately, most of the conductive plastics and rubbers are highly sensitive to temperature changes. Consequently, in transient thermal environments the thermally induced effects may swamp the strain-induced changes.

Gages to measure strains within a grain must possess shear and bulk moduli as similar as possible to those properties of the propellant in which they are embedded.

In selecting gages to measure stresses within a grain, it is necessary to consider embedding gages with an extremely high stiffness compared to that of the propellant. In this case, a signal proportional to stress will be obtained, but the inclusion of a hard element within the grain will distort the local stress field. Unfortunately, when stress measurements are required within a grain, it appears that one must accept this local field distortion and determine its significance by analysis or experiment.

Internal stress and strain measurement must be considered from the point of view that neither an exact compliance match with the propellant properties, nor an infinite mismatch, is feasible. The problem therefore is one of determining the transfer function that relates gage output in the distorted stress field to the stress or strain that would exist in the undistorted field.

Because the attainment of zero primary energy input is impossible, the information measured with even the best of transducers, i. e., one in which the primary energy input has been minimized, is incorrect. The data may be corrected by one of the following methods:

- Mathematically describing the physical phenomena of gage-body interaction so that a given gage output may be corrected by analysis to establish the original free-field stress value.
- Calibration by a one-to-one similitude testing to provide an empirical calibration curve (this method requires either exact duplication of the prototype situation or an approximate or limit analysis, as above, to ensure similitude).

The recommended approach includes performing both the above steps; a rational analysis and model, or similitude calibration, the analysis results being used to verify design and improve the calibration test fixture.

Other forms of energy transfer between the transducer and the system being measured also must be minimized. This is particularly important when employing passive types of transducer, e. g., resistance wire strain gages, which need an excitation current to generate an output signal. The required excitation supply must not be such that considerable energy is dissipated in the gage circuit, otherwise energy loss could occur through local heating effects. Such heating effects could grossly change the parameter being measured.

Similar considerations apply to the use of thermistors for measuring temperature. The dissipation in the thermistor circuit must be maintained at a low level, otherwise self-heating effects will be obtained.

A.4 TRANSDUCERS IN ELASTIC MEDIA

Transducers in elastic media generally are expected to measure one or more of the following scalar or vector quantities:

- Stresses, such as the following:
  - Normal to a given plane
  - Tangent to a given plane
  - Dilatational (or hydrostatic stress)
  - Deviatoric
  - Principal stresses and directions
  - Shear stresses and directions
- Strains, under the above conditions
- Displacement of a point on the body with respect to some reference
- Strain-energy of an element of the body
- Rotation of an element of the body
- Moduli of the body, such as Young's Modulus, Poisson's Ratio, Bulk Modulus, yield point, elastic limit, etc.
- Temperature (and temperature gradient)
- Acceleration forces (and direction)

The performance of a gage embedded within an elastic medium is affected primarily by the following variables:

- Gage geometry
- Gage material constants
- Sensing element (type and location)
- Elastic body geometry and loading
- Elastic body constants (which may or may not be highly temperature sensitive)

The gage response is secondarily affected by the following:

- Temperature gradients and temperature changes (inducing changes in the sensitivity of the sensing element and possibly inducing temperature stresses in the gage itself)
- Possible stray electric or magnetic fields
- Variations (spatial, temporal, or temperature-induced) in the elastic body constants
- Acceleration and vibration body forces in both the elastic body and the gage

- Acoustic effects
- Alignment and directional effects for vector quantities
- Misfit stresses and slack
- Cross-sensitivity effects (for strain elements; shear versus normal effects also)

Most of these effects are amenable either to analysis and proper interpretation, corrective measures in the design of the primary energy input elements, or corrective circuiting for the biasing energy inputs.

Where none of the above measures apply, the gage then is left with an inherent error that can be bounded by proper analysis or calibration.

Transducers may be used in conjunction with a linear elastic material with confidence because there is a unique relationship between the stress and the strain, i.e., the stress is a linear function of the strain. This simple functional relationship enables the data from any type of embedded sensor to be interpreted as either stress or strain with no ambiguity in the data. The fact that a gage is in reality a strain or deformation measuring sensor does not invalidate its use for measuring stress, as the stress is simply a constant factor (E) times the strain.

This situation has existed in nearly all applications of gages and the result has been that methods of use and calibration techniques have been developed for use with elastic materials. Unfortunately, this limitation of existing techniques is not generally understood, and gross errors in gage data interpretation can result. This is especially true when gages are used in conjunction with a viscoelastic material where the stress is no longer a unique function of the applied strain.

A.5 TRANSDUCERS IN VISCOELASTIC MEDIA

The main problem of using transducers in conjunction with viscoelastic media is the lack of a unique relation between the stress and the strain. The stress and the strain in the material, e.g., a propellant grain, can behave in very different ways and it is necessary to understand the differences in their behavior so that the gage data may be accurately interpreted. Also, it is necessary to use strain gages for measuring strain, and stress gages for measuring stress, otherwise large errors can result.

All of the problems previously mentioned apply equally to viscoelastic media transducers. In addition, the problems mentioned below must be considered:

- The time dependence of the viscoelastic media relaxation shear modulus and relaxation bulk modulus
- The extreme temperature sensitivity of the various moduli for polymeric materials
- The effects of real time on the moduli, i.e., aging effects such as oxidative cross-linking, post-cure reactions, and hydrolytic type induced chain scissions.

As a result of the above effects, viscoelastic analysis is somewhat more complicated than the elastic, even for isothermal conditions. Where both spatial and temporal variations of temperature are occurring, the analysis becomes extensive.

It cannot be too highly emphasized that any calibration test or analysis of a transducer in a viscoelastic material that does not include both the stress history of the viscoelastic material, and the temperature history and distribution, will result in grossly erroneous conclusions.

A.6 EFFECTS OF PROPELLANT ON TRANSDUCER RESPONSE

The complete gage-grain interaction problem consists of two separate parts, the influence of the surrounding material (propellant) on the response of the gage, and the effect of the embedded gage on the stress-strain field within the grain. Though these two effects may be considered separately, the interaction problem consists of the sum of these two effects. The effect of mechanical stress or strain on temperature sensing elements, such as thermocouples or thermistors, is in general quite small. Thus the major problem with temperature sensors is the disturbance which they create in the stress-strain field of the grain. Mechanical sensors such as stress or strain gages are influenced by the embedding material, the extent of that influence being a measure of the quality of the gage.

The easiest problem is measuring strains at a free surface of a propellant grain. Providing that the strain gage requires very little force to operate, there will be very little influence of the gage on the propellant surface and virtually no influence of the propellant on the gage. It should be noted that the conventional foil or wire resistance strain gages are not adequate for measuring surface strains on propellant because they require too much force to operate. They are very satisfactory for the measurement of surface strains in metallic objects, e.g., rocket motor cases, where the stiffness of the metallic surface is much greater than that of the gage.

This observation illustrates the point that the absolute stiffness of the gage is not as important as is the stiffness ratio between the gage and the substrate. As an illustration of this effect, the analysis of a diaphragm gage embedded in an elastic material may be considered. This analysis was performed by Professor Fitzgerald of the University of Utah (Ref A-3). The loading conditions considered in the analysis are shown in Figure A-1 and the calculated relative gage response, i.e., the ratio of the gage response in the propellant to the response of the gage in a fluid, is shown plotted versus propellant shear modulus (a measure of the propellant "stiffness") in Figure A-2. At low values of propellant shear modulus equivalent to low propellant stiffness, the gage response is identical to that of the gage to fluid pressure, i.e., the relative gage response is unity. This is true for all three gages considered in the figure. If, however we examine the response curve for the low-stiffness 25 psi gage, it will be found that the relative gage response is reduced as the propellant shear modulus increases. At a value of shear modulus equal to 100 psi, the relative gage response is 0.9, or 90 percent of the fluid response, at a value of 1000 psi shear modulus, the relative gage response is reduced to 0.5, or 50 percent of the gage response in a fluid. As the propellant shear modulus increases to 10,000 psi, the relative gage response is less than 0.1, or 10 percent of the gage response in a fluid.

In practice, therefore, if a stress of 10 psi is applied to the propellant containing the gage, a response signal equivalent to 10 psi will be obtained in a fluid and at low values of shear modulus (1 to 10 psi). A response signal equivalent to only 5 psi stress will be obtained when the propellant shear modulus is 1000 psi, and a response signal equivalent to only 1 psi will be obtained from the gage if the modulus of the propellant is 10.000 psi.

The primary effect of the propellant on the response of an embedded gage is to reduce it below that which is obtained in a fluid. When the ratio of the gage stiffness to that of the propellant is low (a flexible gage in a hard

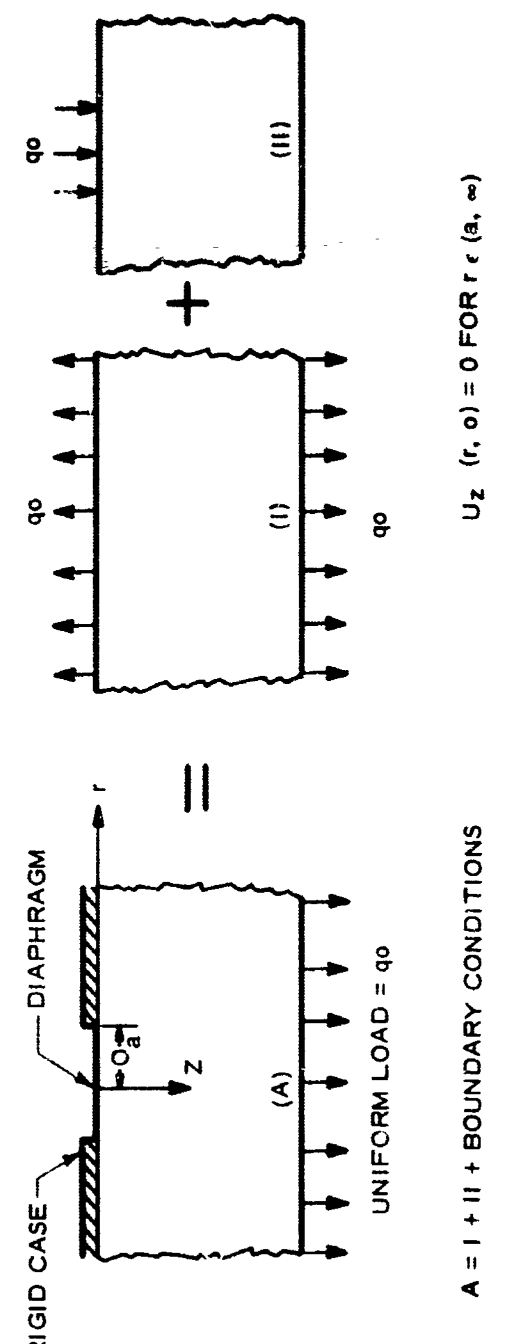


Figure A-1 Superposition of Loadings I for Diaphragm Gage Analysis

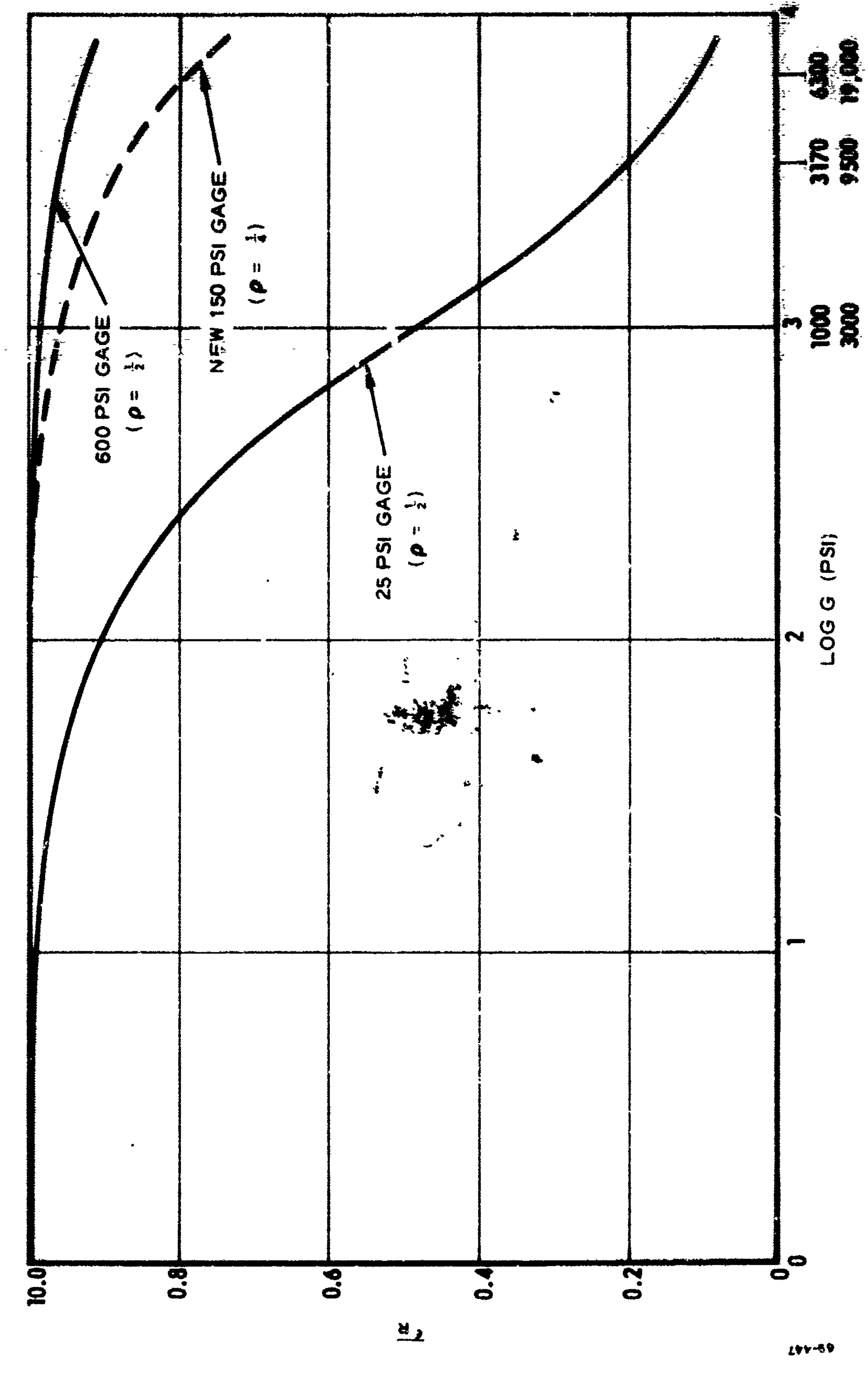


Figure A-2 Gage Output Ratio versus Log Shear Modulus G propellant), a considerable reduction in gage response is produced. Unless this reduction in response is measured before the gage is used, the output of the gage can be misinterpreted, leading to a very large error in estimated stress values. If, for instance, the 25 psi gage readings were taken at face value and the fluid pressure calibration data were used, the applied stress would be underestimated by 50 percent if the propellant modulus were 1000 psi and would be underestimated by 10 times if the propellant modulus was 10,000 psi. These are considerable errors and the improper use of embedded g ge data has resulted in a suspicion of all data derived from such devices. This suspicion is unwarranted if the gage is designed for its purpose and if the necessary calibration steps are performed prior to gage embeddment. The use of the stiffer 150-psi and 600-psi diaphragm gages results in much smaller changes in relative gage response at relatively high values of propellant shear modulus. For instance, Figure A-2 shows that the 150-psi gage response ratio falls to only 0.7 or 70 percent of the fluid response at a shear modulus of 10,000 psi. The response ratio of the 600-psi gage shown even less change with a value of 0.9 or 90 percent at a 10,000 psi shear modulus value.

These results, while calculated specifically for the diaphragm gages, are valid for all types of gage embedded in an elastic material. The precise value of shear modulus at which a 10-percent reduction in response is obtained depends upon the gage construction details, but there is such a modulus value, and the gage response will decrease as the modulus is increased beyond that value.

A.7 EFFECTS OF TRANSDUCER ON PROPELLANT STRESS/STRAIN FIELD

Transducers may be employed between the limits, at one extreme, of rigid inclusion and, at the other extreme, of a void. Effects of the embedded gages on the grain stress/strain field may be assessed by reviewing the analytical results of voids and inclusions in elastic media. The exact effect of a specific type of gage will lie somewhere between the two limit cases, depending on the construction and materials of the gage.

It is shown (Ref A-4 and A-5) that the presence of a circular hole in a thin sheet, when subjected to uniform tension applied in one direction at a distance from the hole, will produce a stress concentration of approximately 3 at the edge of the hole. The curve plotted in Figure A-3 shows that the maximum tension falls rapidly to the mean tensile stress in the sheet and at a distance of 3 times the radius of the hole. Beyond that distance, the sheet is not influenced by the hole. The effect of the hole is very small at a distance of 2 times the radius of the hole. Stress concentrations of this type influence the stress/strain field of the sheet for only a very small distance around the hole. If the size of the hole is small, the disturbance to the stress field also will be small.

The precise magnitude of the stress concentration factor is also dependent on the type of stresses applied to the sheet. For the case of a pure shear field, the maximum stress concentration factor is 4 times the average stress in the sheet. It should be noted that whereas a tensile stress concentration of 3Y occurs at the points marked n in Figure A-3, the stress at the points marked m is compressive and equal to the magnitude of the applied stress

Goodier (Ref A-5) showed that similar stress concentration factors are obtained for the problem of a spherical cavity in a three-dimensional bar subjected to uniaxial tension. Maximum stress concentration factors of 2 were obtained for this problem, but a stress concentration factor of 4 was obtained when a shear field was applied to the bar.

Goodier also showed that a different type of stress concentration factor was obtained when a rigid inclusion was considered. The inclusion adheres to the surrounding material and produces an intensification of the tension (adhesion stress) at A, A′, Figure A-4, in the same direction as the applied tension. A peak stress-concentration factor of 2 is obtained for a rigid spherical inclusion in a uniaxial tension field. The stress at the points marked B, B′, becomes compressive and equal to one-half the applied stress, for Poisson's ratio equal to 0.5.

The rigid inclusion produces no appreciable stress intensification of a shear field.

The results of these analyses show that stress concentrations around embedded gages will vary appreciably, depending on the type of material used and the construction and shape of the device. The precise stress strain field surrounding the gage has to be determined for each gage type and for

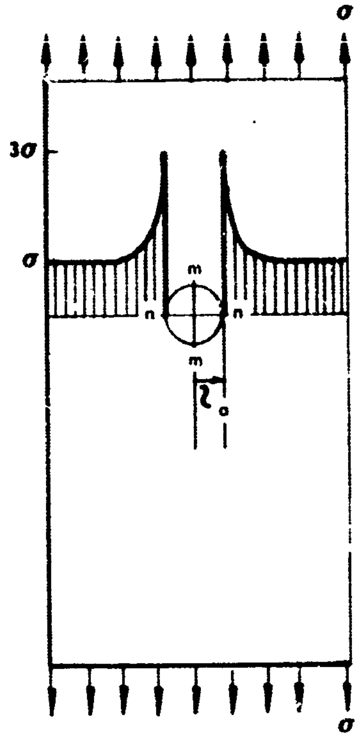


Figure A-3 Stress Concentration Around Hole in Sheet Subject to Simple Tension

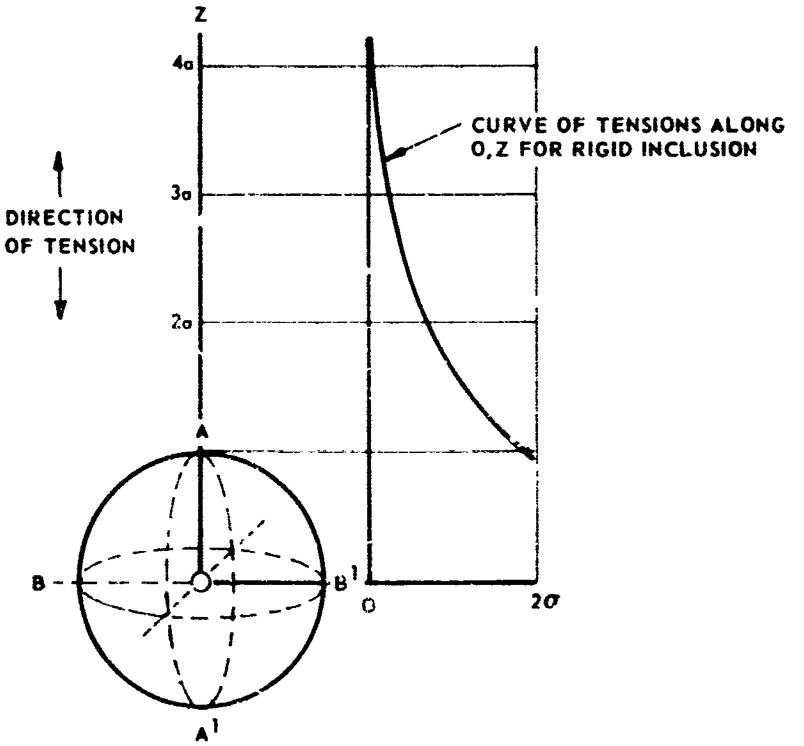


Figure A-4 Stress Concentration Around Rigid Spherical Inclusion in Bar Subject to Simple Tension each application. However, the most important result of these stress concentration analyses is that the stress field is disturbed for only a very small distance around the gage. At distances greater than about twice the radius of the gage from the gage, the stress field is unchanged. This finding is of great importance in developing calibration techniques for gages.

Professor Pister's analysis of a 25-psi diaphragm gage embedded within a bond-in-tension fixture (Ref A-3) may be used to illustrate the effects of a gage upon the stress distribution in the specimen. Figure A-5 shows the axial tensile stress across the baseplate of the specimen when a uniaxial tension is applied to the system. The marked reduction in axial stress across the gage diaphragm is evident. The reduction in stress becomes progressively more pronounced as the propellant modulus increases from 100 to 1000 psi. Analytical results also show that the gage disturbs the stress field for only a small distance around the gage itself.

Figures A-6 and A-7 present the results of Professor Pister's analysis of the 150-psi gage embedded in the uniaxial test fixture for axial loading and for hydrostatic loading. The variation in the axial stress across the diaphragm with the different propellant modulus values is readily apparent. Also apparent is the fact that the gage is subjected to different stress levels under uniaxial loading and hydrostatic loading at the same modulus level.

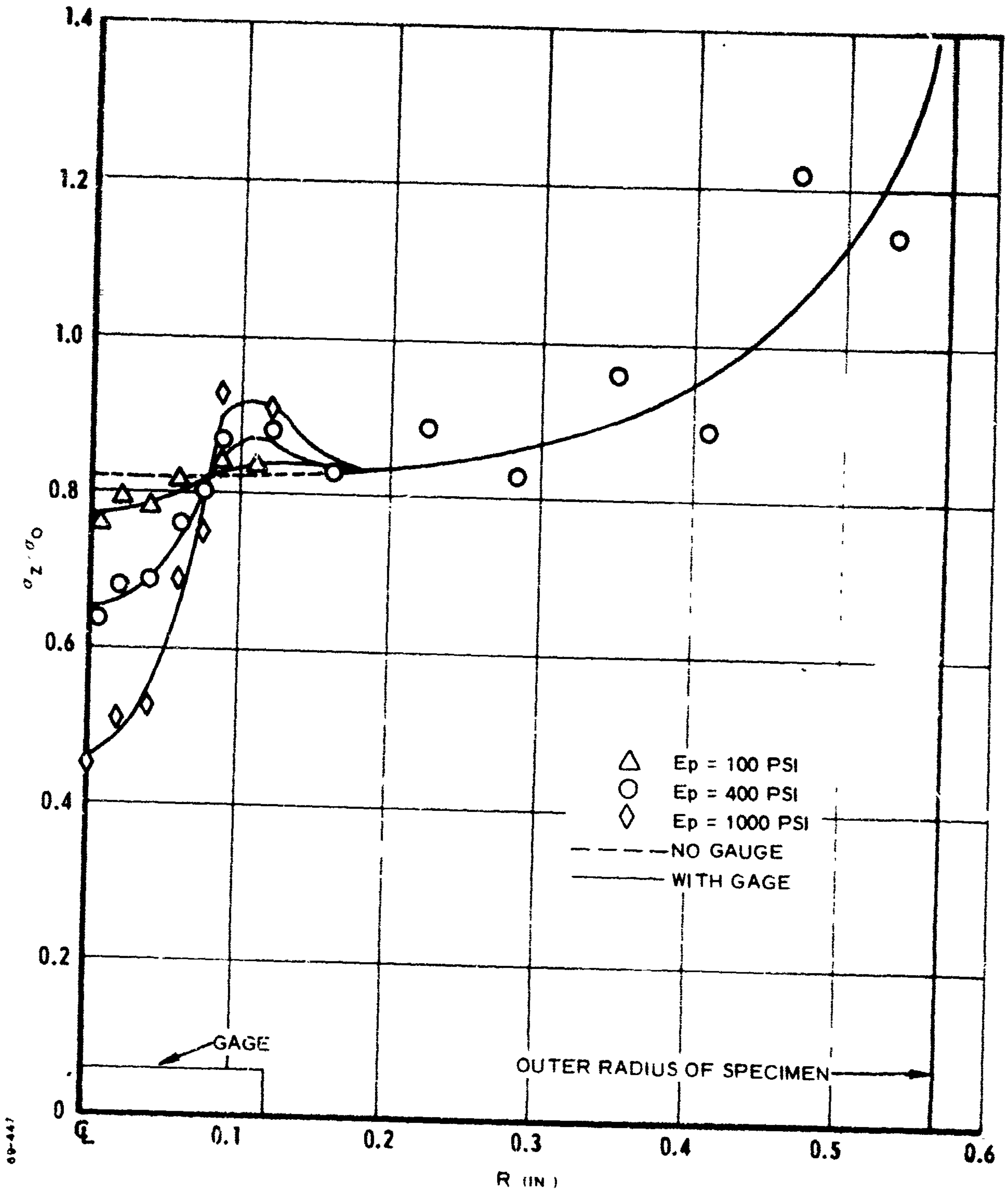


Figure A-5 25-psi Diaphragm Gage in Bond-in-Tension Specimen: Normalized Axial Stress at Gage Level

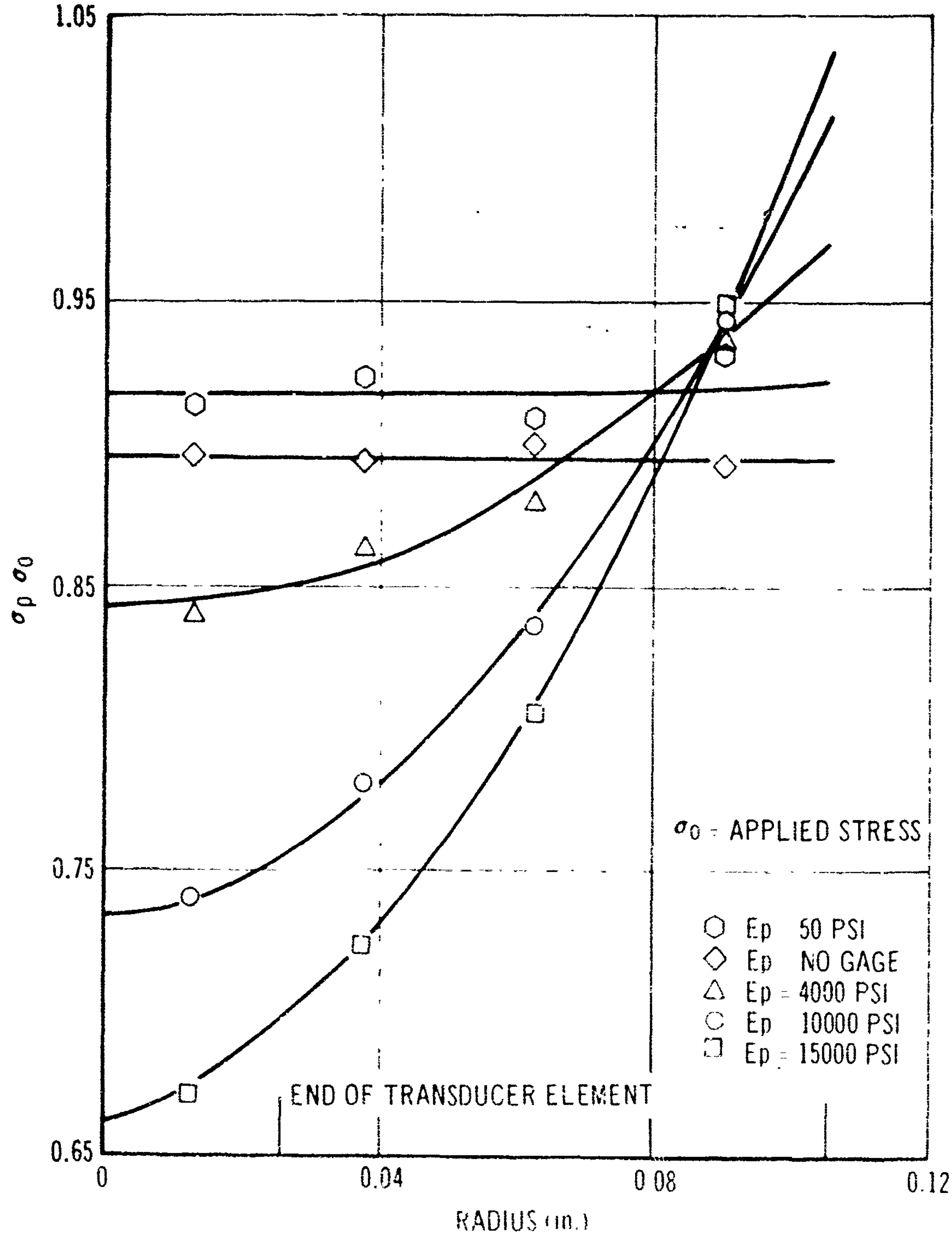


Figure A-6 150-psi Diaphragm Gage in Uniaxial Calibration Fixture under Axial Load

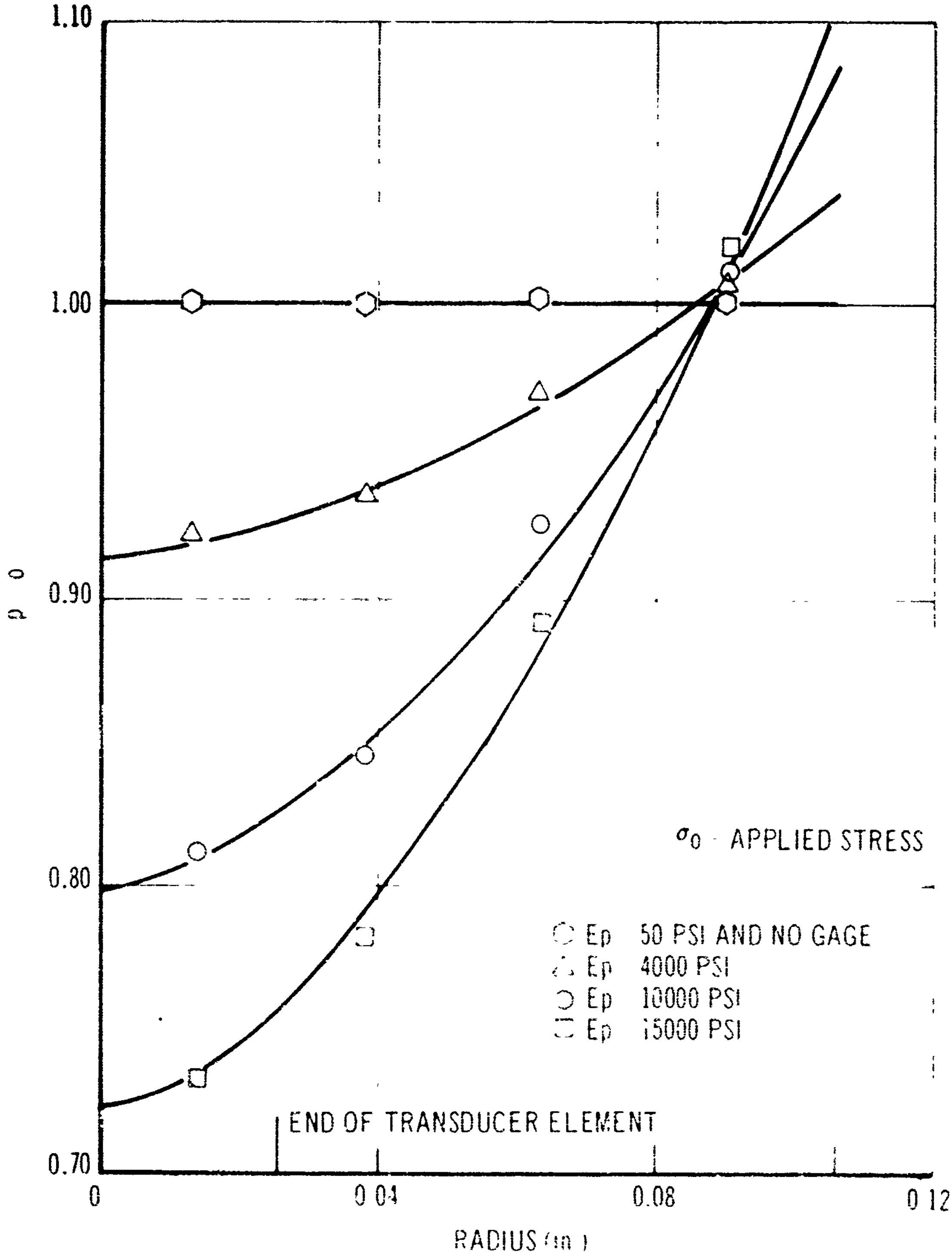


Figure A-7 150-psi Diaphragm Gage in Uniaxial Calibration Fixture under Hydrostatic Load

REFERENCES

A-1 Stein, P. K., "A Unified Approach to Measurement Engineering Through a Revised Transducer Classification Scheme," presented at 19th International Instrument Conference, New York, N. Y., October 1964

A-2 Neubert, H. K. P., "Instrument Transducers," Oxford Press, 1963

A-3 Leeming, H., et al, "Final Report Solid Propellant Structural Test Vehicle, Cumulative Damage and Systems Analysis," Lockheed Propulsion Company Report No. 838-F, Technical Report No. AFRPL-TR-68-130, October 1968

A-4 Timosheako, S., "Strength of Materials, Part II: Advanced Theory and Problems," D Van Nostrand Company, Inc., pp. 312-361, 1941

A-5 Goodier, J. N., "Concentration of Stress Around Spherical and Cylindrical Inclusions and Flaws," APM-55-7

A-6 Leeming, H., et al, "Final Report Solid Propellant Structural Test Vehicle and Systems Analysis," Technical Report No. AFRPL-TR-70-10, Lockheed Propulsion Company Report No. 966-F, March 1970

Appendix B
TRANSDUCER CALIBRATION

B.1 GENERAL APPROACH

The sensors for measuring stress, strain or temperature in a propellant grain produce an electrical output signal that must be related to the desired input information. The presence of the devices in or on the surface of the grain disturbs the stress/strain field locally, and although the sensor provides an output under load, this is a function of the local stresses and strains around the sensor. What is required is the relationship between the sensor's electrical output and a specified component of the stress or strain field that would exist in the grain if the sensor were not there. This, then, is the goal of the transducer calibration tests.

The calibration tests may be performed in special fixtures designed to produce simple stress fields. These enable a thorough evaluation of a specific gage type. Unfortunately, in many cases it is not possible to remove a transducer from the fixture after calibration without great risk of damage. Therefore, in addition to these laboratory calibration procedures, in situ calibration techniques are also required. These in situ tests then will provide the calibration data for a particular transducer embedded in a specified location within a grain.

The transducer-grain interaction studies have demonstrated that we cannot regard the embedded sensor alone as the measuring transducer. The system, including the propellant surrounding the embedded gage and any case material to which the gage may be attached, must be considered in an adequate calibration procedure. The mechanical and thermal effects of the propellant on the embedded sensor must be determined before the device is used. The calibration data supplied with the sensor by the manufacturer must be replaced by new data generated under realistic conditions, i.e., with the gage embedded in propellant.

B.2 ERRORS AND INACCURACIES IN ELECTROMECHANICAL SENSOR DATA

Before a thorough evaluation and calibration procedure for a transducer in conjunction with propellant is considered, the device itself should be closely examined to make certain that it is suitable for use as a stress or strain sensor. Thus, factors such as the following must be reviewed before accepting a transducer system:

(1) Transducer temperature compensation for sensitivity and zero drift

(2) Transducer and electronic recording equipment reproducibility

(3) Long-term stability of transducer signal (includes a drift in power supply)

In general, transducers manufactured by a competent instrument maker will have been properly temperature-compensated before delivery. In fact, limits for acceptance will form a part of the specification.

However, it must be appreciated that factors such as the thermal zero drift of the sensor alone, or the usual minute inaccuracies inherent in modern electro-mechanical sensors, will be of no great importance once the device is embedded in propellant. Typical changes in thermal zero shift with temperature, and changes in sensitivity caused by embedment, will be discussed later in this appendix.

The following subsection discusses briefly the factors to be considered if predictive calibration is the important application, i.e., the gage is to be used to measure field quantities in a prescribed thermal, but unknown mechanical environment.

B.3 PRINCIPLES OF GAGE CALIBRATION*

B.3.1 Introduction

To clarify the nature of problems associated with gage calibration, it is convenient to think of the gage and the embedding material as a "black box" or a system, as depicted in Figure B-1. The gage, surrounded by an embedding material, is subjected to certain thermomechanical histories, including stress, strain, and temperature. If one imagines that the gage and embedding material are separated at their interface, it is apparent that the gage output (voltage) depends, in some fashion, on the deformation and

*By Professor Karl Pister, University of California, for Mathematical Sciences, Northwest (Ref A-6)

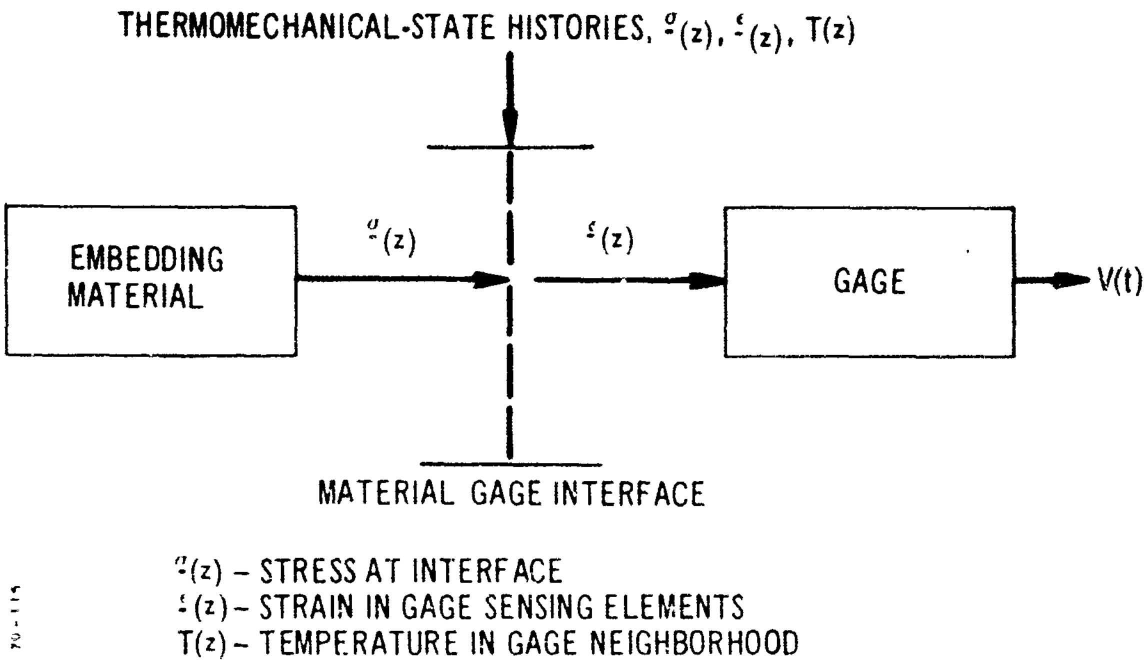


Figure B-1 Gage Imbedding Material System temperature of the gage elements irrespective of the nature of embedding material. This leads to the basic proposition, presented in Equation B-1, governing the gage system function. On the other hand, it is equally apparent that the gage deformation is linked directly to the stresses acting on the material/gage interface. These stresses will depend upon the properties of the embedding material and the gage. As a result, calibration in a practical sense cannot be separated from material characterization and material response in a given calibration fixture. The following sections address the problems mentioned above.

The following proposition governing gage behavior can be adopted:

The voltage output of a measuring device (gage) is determined by the history of strain and temperature in a neighborhood of the gage. In other words, the voltage at time, t, is the value of a functional of strain and temperature in a neighborhood of the gage. This can be expressed symbolically as

$$V(t) = \mathop{F}_{s=0}^{t}\left[\epsilon(s),\ T(s)\right] \text{ in } N. \qquad \text{(B-1)}$$

where $V(t)$ is the voltage output, ϵ is the strain tensor, and T the temperature in some neighborhood, N, defined by the gage. The functional F will be called the "gage transfer functional." In the sequel, Equation B-1 shall be limited to the special case where the gage is composed of nonhereditary elements, i.e., its response is elastic. In this instance, Equation B-1 takes the form

$$V(t) = F\left[\epsilon(t),\ T(t)\right] \qquad \text{(B-2)}$$

where F now denotes the "gage transfer function." To proceed further, the functioning of typical gages must be examined briefly so that the notion of gage neighborhood and the role of the strain tensor in Equation B-2 can be defined. This will be accomplished for two examples: the diaphragm type contact gage and the embedded filament gage.

In a typical diaphragm gage for small displacement of the diaphragm, the voltage output depends primarily upon the rotation of the end-points of the transducer bonded to the diaphragm. The strain tensor appearing in Equation B-2 thus occurs in a particularly simple way in the transfer function. The diaphragm rotation depends upon the magnitude and distribution of the normal stress acting upon the diaphragm (and to a much lesser extent, upon the shearing stress also). Accordingly, in this instance the gage neighborhood is defined by the contact surface between the diaphragm and the surrounding medium. In the special case of a fluid at rest, shearing stresses vanish and a uniform normal stress acts on the diaphragm. Consequently, the voltage output is easily related to normal stress at the gage. In the case of a gage bonded to a deformable solid, however, the problem of relating transducer endpoint rotation to interface stresses is much more complicated in that thermomechanical properties of the material are involved. This difficulty constitutes the major obstacle in gage calibration for use in deformable solids.

As a second example, consider a single filament of finite length embedded in a solid. The voltage output depends on the change in length of the filament, which is proportional to some average strain over the length. If the length is small, or the extensional strain gradient small, the average is a significant quantity. In this instance the gage neighborhood is the set of points defining the filament.

Once again, the strain tensor, $\underset{\sim}{\varepsilon}$, appearing in the gage transfer function occurs in a simple way: the gage voltage depends upon extensional strain along the filament. However, in the present case, the average extensional strain depends upon all components of the stress tensor in the gage neighborhood. In addition to a knowledge of thermomechanical material properties for the solid, a sufficient number of independent filaments with a "common" neighborhood is required to calibrate the gage.

To summarize this section, the following points are observed:

- From the mechanical design of the gage, the gage deformation (related directly to the strain field in the surrounding solid) can be expressed in terms of voltage output
- From a knowledge of the mechanical properties of the surrounding solid, gage deformation can be related to stress components in the gage neighborhood
- A sufficient number of independent gages must be employed to provide data for determining the unknown stress components

The manner in which gage calibration is related to material properties of the embedding material will be discussed in the following subsection.

B.5.2 Material Characterization and Gage Calibration

As mentioned previously, the problem of gage calibration for a gage embedded in a solid depends upon a complete knowledge of the thermo-mechanical properties of both the gage material and the solid. That this is so, is evident if the fact is considered that the contact between gage and solid is continuous and that in a particular application the stress and strain state in the gage neighborhood is statically indeterminate. Furthermore, from a practical standpoint, it is impossible to produce an experiment in which the stress, strain, and temperature for the gage neighborhood are controlled, known variables. Therefore, true calibration can only be obtained indirectly by a combination of analysis and experiment. Such a scheme employs a test fixture incorporating gage and solid in a way that stress, displacement, and temperature are controlled on the boundaries of the fixture. For these specified boundary histories, the gage output is recorded. The problem that remains is to relate the boundary histories to gage neighborhood histories. The device for accomplishing this is a mathematical boundary value problem. The solution of such a problem relates the boundary and gage neighborhood stress, strain, and temperature histories to the gage output, provided that the mechanical and thermal properties of the gage and solid have been completely determined for the range of interest. Furthermore, by solving the same boundary value problem of the test fixture with the gage removed, the "free field" mechanical state at the gage neighborhood can be found. From this information, the extent of gage interference can be determined.

Returning now to the gage transfer function defined in Equation B-2, the diaphragm gage is taken as an example. From knowledge of the thermo-mechanical properties of the gage and solid and solution of the boundary value problem for a given test fixture, the normal stress in the gage neighborhood can be calculated. The average normal stress can be calculated for the gage neighborhood, and this value used to calibrate the gage for experimentally determined voltage outputs for the given test fixture. In addition to dependence upon temperature, the calibration depends upon the properties of the solid for the stress state and temperature associated with the text fixture. This is an extremely important point to grasp because utilization of the gage presents an inverse problem: i.e., given the transfer function and the gage output, determine the diaphragm normal stress, assuming temperature is obtained by independent measurement. Clearly the inverse problem has a solution with meaning only if applied to a situation closely resembling that of the calibration fixture in the gage neighborhood.

B.3.3 Gage Calibration for Elastic Solids

Inasmuch as state-of-the-art analysis of solid rocket motors relies primarily on linear, elastic analysis, a reasonable point of departure is to assume that the embedding solid is linear, isotropic elastic. This implies that two elastic constants and two thermal constants characterize the material. In the case of an incompressible solid, only one elastic constant is required. With this information in hand, along with a prescribed test fixture such as a uniaxial jig for a diaphragm gage, the gage can be calibrated. For an elastic solid, the voltage output is a function of normal stress in the gage neighborhood, temperature, and solid mechanical properties:

$$V(t) = F\left[\sigma_{zz}(t),\ T(t),\ E,\ \nu\right] \tag{B-3}$$

and for a linear gage, this reduces to

$$V(t) = K\left[E,\ \nu,\ T(t)\right]\, \overline{\sigma}_{zz}(t) \tag{B-4}$$

where $\overline{\sigma}_{zz}$ is an average normal stress over the gage neighborhood and K is the gage transfer constant for the particular solid in the given test fixture. This equation is easily inverted to express normal stress as a function of gage output. It is essential to recognize here that K may depend upon temperature as well as upon the elastic constants of the solid. However, for a well designed gage, the dependence of solid properties may be slight.

The significant material parameters affecting calibration actually are the modulus of elasticity of gage and solid and their respective Poisson's ratios. The calibration can be effectively studied in terms of the quantities E/E_g, ν, ν_g.

For problems with variable temperature, the dependence of K and T must be determined experimentally, as well as a correction made to incorporate temperature compensation corrections, if any. Observe here that the transfer constant, K, depends explicitly on the type of calibration fixture employed. For example, if a gage were mounted on a surface at which simple shearing deformation occurred, K would be equal to zero. It is important to establish the range of stress states over which K adequately defines the transfer function. Uniaxial test jigs subjected to hydrostatic pressure and tension provide examples of such extensions.

If a nonlinear elastic solid model is used for the solid, the calibration procedure differs in the following points: material characterization is complicated by the fact that for an isotropic solid, three material functions are required in place of two constants (two functions for an incompressible material). Furthermore, the boundary value solution relating mechanical input to the test fixture and gage neighborhood stress now is nonlinear. Solution schemes are more involved and numerical results less well defined.

In the discussion above it has been tacitly assumed that a solution method for the boundary value problem also is available. Because of the complexity of most gage calibration fixtures and gage applications, an approximate numerical scheme is necessary. As a result, an additional source of uncertainty is introduced in the problem, both from errors in the approximate solution as well as from the numerical analysis neighborhood introduced by any discretization technique such as a finite difference or finite element method.

B.3.4 Gage Calibration for Linear Viscoelastic Solids*

The calibration procedure required for solids that are linear, isotropic viscoelastics is essentially the same as for an elastic solid. In place of two elastic constants, there now appear two functions of time (creep or relaxation moduli) for isothermal characterization. The test fixture input now is a history of boundary traction and displacement. The solution of the test fixture boundary value problem relates this input history to the gage neighborhood stress history, which in turn produces the values of voltage output. In a typical mixed boundary value problem for a test fixture, the spatial distribution of stress (hence gage calibration or gage transfer function)

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* For a more comprehsnsive review of gage calibration in a viscoelastic material see the Third-Year Final Report, Structural Test Vehicle Program, to be published December 1971.

depends explicitly on the viscoelastic material functions, which depend on time. The significant parameters affecting the transfer function are now $E(t)/E_g$, $\nu(t)$, ν_g. In typical viscoelastic solids, the variation in $E(t)$ may amount to many orders of magnitude. Accordingly, calibration must be approached much more carefully. Experiments and numerical analyses must be conducted over a sufficiently wide range of conditions of time and temperature to permit proper calibration. Experience with calibration for elastic solids suggests that the gage transfer function is fairly insensitive to the ratio $E(t)/E_g$ over certain ranges. In conducting experiments in which temperature changes are introduced, it is desirable that thermal equilibrium be attained before calibration. Temperature gradients in the fixture will introduce nonhomogeneity in material properties, thus complicating the relation between boundary input data and gage neighborhood stresses.

B.3.5 Gage Interaction Problem

In the introduction, it was mentioned that every gage creates its own field or perturbation of the mechanical field that is to be measured. Accordingly, the calibration procedures described above are by themselves inadequate to permit predictive information to be obtained. To complete the total calibration procedure, the gage field must be determined for each test fixture and experiment so that it can be subtracted from any future use of the gage for prediction. Once again this involves the formulation and solution of mathematical boundary value problems. The calibration experiments must be resolved with the gage removed to calculate the perturbation of the mechanical fields produced by the presence of the gage. This perturbation subsequently must be subtracted from all future predictions of stress and strain states made by the gage. It must be recognized again that the perturbation depends on the test fixture configuration, as well as upon the type of loading of the fixture. For this reason, care should be exercised in selecting fixtures which produce stress fields representative of intended application of the gage.